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On Implementation and Analysis of Stability Calculations of the New Polar Code

Thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Technology.

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Tiivistelmä

IMO:n kehittämä Polarkoodi on tullut voimaan vuoden 2017 alussa. Se tuo mukanaan lisää vaatimuksia, jotka koskevat polaari alueiden aluksia. Arktisilla ja Antarktisilla vesillä liikuttaessa kylmyys, jää ja infrastruktuurin puute lisäävät riskejä. Uudet vaatimukset on tarkoitettu ennaltaehkäisemään riskejä, sekä parantamaan onnettomuudesta selviytymistä lisäämällä vaatimuksia laivan suunnitteluun ja varusteluun. Polarkoodi asettaa myös lisävaatimuksia ympäristön suojeluun. Polarkoodi velvoittaa kaikkia aluksia, joilla operoidaan Arktisilla tai Antarktisilla alueilla, hankkimaan 'Polar Water Certificate' -todistuksen joka todistaa laivan ja sen miehistön täyttävän Polarkoodin vaatimukset.

Tämä tutkimus keskittyy Polarkoodin neljänteen lukuun, joka koskee laivan vakavuutta ja osastointia. Tutkimuksen aihe kattaa kaksi sääntöä: ehjän laivan vakavuus jään kertymisen seurauksena, sekä vaurioituneen laivan vakavuus jään aiheuttaman vaurion vuoksi. Tutkimuksen tarkoitus on (1) käsitellä molempien sääntöjen taustoja ja historiaa, (2) kehittää laskentatyökalu sääntöjen mukaisten tilanteiden luomiseen ja laskentaan ja (3) analysoida vakavuus sääntöjen vaikutusta tapaustutkimuksen avulla. Jotkin Polarkoodin säännöt ovat monitulkintaisia ja ennakkotapauksia tulkinnoista ei ole julkisesti saatavilla. Tästä syystä tutkimus tarjoaa tulkintatavan vauriovakavuus -säännölle, jotta laskentatyökalun kehitys on mahdollista. Työ antaa myös laajemman kuvan Polarkoodin muista vaatimuksista, keskittyen kuitenkin pääasiassa vakavuussääntöihin.

Onnettomuuden seuraukset ovat luonnollisesti vakavampia niille laivoille jotka ei ole täysin Polarkoodin mukaisia, kuin niille jotka on suunniteltu täysin sen mukaisesti. Vauriovakavuutta koskeva sääntö ei ole pakollinen olemassa oleville laivoille. Tämän vuoksi vauriovakavuuden tapaustutkimus onkin mielenkiintoinen olemassa oleville laivoille, paljastaen miten tällainen laiva selviäisi Polarkoodin mukaisesta jäävauriosta.

Työn tuloksena säännöt ja niiden vaikutus esimerkkilaivoihin selviää. Jään kertymisen arvot ovat alun perin tarkoitettu kalastusaluksille, mutta ovat kohtuullisia myös isommille aluksille. Vauriovakavuuden suhteen selkeää selitystä jäävaurion mitoille ei löytynyt, mutta käytetyt mitat ovat tutkimuksen mukaan riittävät. Tässä työssä kehitetyt menetelmät jään kertymisen ja relevanttien jäävaurioiden luomiseen mahdollistivat tapaustutkimukset, joiden perusteella jään kertyminen ei ole riski tutkituille aluksille. Jäävauriot puolestaan osoittautuivat kriittisiksi tutkitulle, SOLAS 2009 mukaisesti suunnitellulle risteilijälle jonka 1589 relevantista vauriosta 13 ei toteuttanut Polarkoodin vaatimusta vauriovakavuudelle.

Avainsanat Polarkoodi, vauriovakavuus, jäävaurio, ehjän laivan vakavuus, jään kertyminen

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Abstract

The Polar Code developed by IMO became in to force at the beginning of 2017. It brings more requirements for ships navigating in the polar waters where coldness, floating ice and remoteness to infrastructure poses special risks compared to open waters. The new requirements are focusing to accident prevention and survivability after accident with the means of proper ship design, crew skills and survival equipment. Polar Code requires also methods for the protection of polar environment. Polar Code requires all ships that are intended to navigate at the polar waters to have Polar Water Certificate, which proves that the ship and its crew fulfils the relevant requirements.

This study focuses on the chapter four of the Polar Code, concerning ship stability and subdivision. The topic covers two requirements: intact stability due to icing and damage stability due to ice-related damage. The aim of this thesis is to (1) assess the background of these requirements to enlighten where these requirements come from, (2) develop calculation tools for studying these stability scenarios and (3) analyse the effect of the stability requirements with example cases. The interpretation of Polar Code is still somewhat unclear due to ambiguous phrasing and lack of precedent cases. The thesis offers a way for interpreting the damage stability requirement. This selection of interpretation is needed for the calculation tool. In addition, this thesis provides overall view on Polar Code requirements, but focusing mainly on the stability requirements.

The risk of accident at polar waters is naturally higher with existing ships that are not in accordance with all Polar Code's requirements. The damage stability requirement is not mandatory for existing ships, whereas the icing rule is. Thus analysing a pre-Polar Code ship contributes interesting results since the Polar Code's damage stability case is not taken into account when existing ships are designed and built. However it is possible for existing passenger ship to acquire polar ship certificate and start cruising in the polar areas, and in the worst case experience ice-related damage.

As a result of the work the rules and their effect on studied ships is revealed. Ice accretion vales are originated from fishing vessel rules, but are adequate for larger ships. The background of extents used in ice damage remained unsolved. However the extents revealed to reasonable. The developed tool worked as intended and enabled case studies. The case studies indicated that icing is not big risk for existing ships. However, the studied SOLAS 2009 design passenger was revealed to be vulnerable for ice related damages in 13 of 1589 damage scenarios that fulfil the damage extents as defined in Polar Code.

Keywords Polar Code, damage stability, intact stability, ice damage, icing

Acknowledgements

This master thesis studies the newly released Polar Code. As it sets new safety criteria for ships, it is interesting topic to be studied for me and NAPA Ltd. As the aim of the study is to implement calculation methods and study the effects of these criteria, the topic is relevant for NAPA and safety of winter navigation in general.

I would like to thank my advisor Dr. Pekka Ruponen for pointing me to the right directions with his very good advices and thoughts on the subject. I would like to equally thank all my colleagues at NAPA Ltd. who have been helping and supporting me through the process of making this thesis, without them this would have been much harder. Gratitude belongs to NAPA also for its financial support to enabling the writing of this thesis.

I am also grateful to my supervisor Professor Pentti Kujala for his thoughts and guidance, especially pointing at the right direction at the beginning of the work as the topic was still developing. Special gratitude goes also for Mr. Henning Luhmann (from Meyer Werft ,Papenburg) for giving permission to use their passenger ship model for the case study calculations included in this thesis. A thank you belongs to also Mr. Mika Hovilainen and Mr. Maximilian Vocke (Aker Arctic Ltd.) for giving a very helpful interview about the topic.

Last but not least I would like to thank my parents for raising me to become what I am today, and my fiancé Eevi for all her support and encouragement.

Winter navigation has been interesting field of study for me through the time maritime studies. Following the long traditions of Finnish expertise in the field of winter navigation by making this master's thesis has been very interesting and instructive journey. Big part of these traditions are close relationships of the naval architects in the industry, tied already during the time of studies in LRK and lasting further into life, as I have seen. This is one of the best parts of the trade.

In Helsinki 31.07.2017

Timo Huuskonen

Contents

Acronyms

A	Attained index
A_{D1}	Area of the calculation section below the deck in question
A_{D1}	Area of the calculation section above the deck in question
A_s	Partial attained index for deepest subdivision draught
A_p	Partial attained index for partial subdivision draught
A_l	Partial attained index for light service draught
B	Breath of the ship is the extreme width from outside of frame to outside of frame at or below the deepest subdivision load line
CoG	General expression for center of gravity
CoG_d	Center of gravity of deck in question, also known as centroid
CoG_{DA1}	Center of gravity the calculation section below the deck in question, also known as centroid
CoG_{DA2}	Center of gravity the calculation section above the deck in question, also known as centroid
CoG_{ice_n}	Center of gravity the ice accumulated on ship, where n=(X,Y,Z)
GM	Metacentric height
GZ	Righting arm lever, horizontal distance between the lines of buoyancy and gravity
GZ_{mX}	Maximum positive righting lever, in meters, up to the angle θ_V
$DCoG_n$	Center of gravity coordinate n of the all exposed deck areas combined, where n=(X,Y,Z)
$HPHI$	Notation for GZ curve
K	Constant used in calculation of s_i, depending on ship type and θ_e
L	Length of ship is the length measured between perpendiculars taken at the extremities of the deepest subdivision load line
$LCoG_n$	Center of gravity coordinate n of the lateral projection of the ship, where n=(X,Y,Z)
Length pp	Length between perpendiculars
LOA	Length overall
N	$N_1 + 2N_2$
N_1	Number of persons for whom lifeboats are provided
N_2	Number of persons (including officers and crew) the ship is permitted to carry in excess of N_1
R	Required index, generic entry
R	Value of R as calculated in accordance with the equation in subparagraph 2.2 in SOLAS Regulation 6

R_0	Value of R as calculated in accordance with the equation in subparagraph 2.1 in SOLAS Regulation 6
UIWL	Upper ice waterline of the ship
X	X-axis of right-handed coordinate system, positive direction fore
Y	Y-axis of right-handed coordinate system, positive direction port
Z	Z-axis of right-handed coordinate system, positive direction up
i	Index of compartment or group of compartments under consideration
m_l	Ice mass on the lateral projection
m_d	The ice mass on all exposed decks
p_i	Probability that only the compartment or group of compartments under consideration may be flooded
s_i	Probability of survival after flooding the compartment
θ_e	Equilibrium heel angle in any stage of flooding, in degrees
θ_V	Angle, in any stage of flooding, where the righting lever becomes negative, or the angle at which an opening incapable of being closed weathertight becomes submerged

Abbreviations

ABS	American Bureau of Shipping (Classification society)
BV	Bureau Veritas (Classification society)
CCS	China Classification Society
DNV	Det Norske Veritas (Classification society)
DB	Double bottom
FTA	Finnish Transportation Agency
FSICR	Finnish-Swedish Ice Class Rules
GL	Germanischer Lloyd (Classification society)
IACS	International Association of Classification Societies
IMCO	Inter-Governmental Maritime Consultative Organization (Name changed in 1982 to IMO)
IMO	International maritime organization
IS CODE	The Code on Intact Stability
KRS	Korean Register of Shipping
LBMA	Liberian Bureau of Maritime Affairs
LR	Lloyd's Register (Classification society)
LRK	Laivanrakentajain kerho (Ship builders' club)
MARPOL	International Convention for the Prevention of Pollution from Ships
NAPA	Naval Architecture Package, ship design software by NAPA Ltd.
NKK	Nippon Kaiji Kyokai (Classification society)
OSV	Offshore supply vessel
OTKES	Onnettomuustukintakeskus/Finnish agency for accident research
PRS	Polski Rejestr Statków (Classification society)
Relevant damage case	Possible damage case, fulfilling Polar Code damage extents
RINA	Registro Italiano Navale (Classification society)
RMRS	Russian Maritime Register of Shipping
SOLAS	International convention for the Safety of Life at Sea
TRAFI	Finnish transportation agency

1 Introduction

1.1 Background

Navigating in ice-covered waters has been part of shipping for centuries. The navigation in these conditions started by ice strengthened sailboats that were even capable of ice breaking in some extent. Before this, the indigenous people of the arctic regions have been exploring these areas in search for food and other resources. (Arctic council 2009) Norwegian sailboat FRAM was one of the first purpose built ships intended especially for polar explorations with its round and strong wooden hull. Purpose of the round hull was to lift the ship on top of the ice as the ice pressure increased along the hull. The hull was made to more than 50 cm thick to withstand the ice pressure, but also to insulate the hull. (Nansen 1897) Under the command of Fridtjof Nansen on 1893-1896, expedition group intended to freeze the ship into the polar ice in the eastern Arctic Ocean, and then let the trans-polar current slowly drift the ship towards the geographical North Pole. Attempt failed, as the FRAM and the crew did not reach the pole solely by drifting with the ice, but the interest towards arctic waters kept increasing. Already on 1878, Adolf Erik Nordenskjold was the first to navigate through the Northeast Passage with his sailboat Vega that also had small 20-horse power steam engine in addition to its sails to push forward (Blåfield 2016). The Northwest Passage remained undiscovered until 1906 when another Norwegian explorer Roald Amundsen managed find the way to the Pacific on his three-winter-long expedition (Arctic Council 2009).

Engine-powered ice going ships have been purposely built for ice breaking since 1837 as the city of Philadelphia ordered a ship, named City Ice Boat No. 1, capable of breaking ice and keeping city port and Delaware river open during cold winters. The City Ice Boat No. 1 was operational until 1917 thus having operational life of 80 years (Oesterle 1988). Icebreakers have been the primary way for navigating through ice and making channels for commercial vessels trough the 20th century, ensuring that people and goods are moving even in difficult ice conditions.

From the late 20th century until today, the trend has been going towards more independently moving ice going vessels. In the polar waters, continuous or even irregular icebreaker assistance is not always available. Thus vessels need to be designed in a way that they can navigate more independently trough ice covered waters, using for example double-acting ship concept, where bow is designed for open water and the stern is shaped for ice breaking purposes, allowing typically cargo ships to sail more independently on ice infested waters. (Juurmaa et al. 2001) (Kujala & Riska 2010)

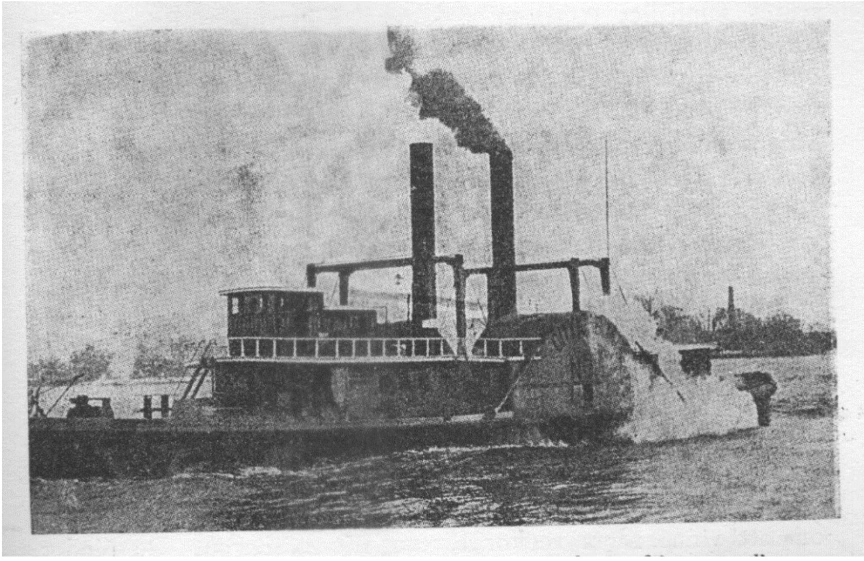

Figure 1. City Ice Boat No. 1 (Wikimedia/Edward O. Clark)

Navigation in open seas and shipbuilding did not have any common rules up until 1912. Safety of ship designs were on the responsibility shipyards and naval architects' personal experience. In 1912 passenger ship RMS Titanic encountered an iceberg collision where 1517 lives were lost. This accident raised international concerns about safe ship designs, and thus uniform rules were introduced to shipbuilding to increase the safety of ship operations and enable safer ship design at shipyards worldwide. This was the starting point for the international convention for the Safety of Life at Sea, noted hereafter as SOLAS, which is international agreement obligating flag states to ensure that ships under their flag are fulfilling the safety requirements. In short, SOLAS agreement requirements concerns ships' construction, equipment and operation at sea. (IMO 2014). Original SOLAS treaty was focused on lifeboat capacity and other safety equipment since many lives could have been saved in the RMS Titanic's accident if there would have been enough lifeboats. Later SOLAS introduced also requirements for other parts of ship design such as structures and stability.

The damage stability requirements were introduced first time on 1948 as SOALS included regulation 7 under chapter 2, regarding "*Stability of Ships in Damaged Condition*". The rule covered deterministic damage cases of up to two adjacent compartments. (IMCO 1948) Damage stability rules were later updated on 1974 to include more detailed deterministic damage scenario having predetermined longitudinal extent (IMO 1974). In 1990 SOLAS was updated to take account also stages of flooding (IMO 1990). Latest major change in SOLAS stability regulations is the introduction of probabilistic damage stability concept which focuses on probabilities on the risks of operation, damage location and survival after damage. The approach of probabilistic damage stability is generally seen to represents the rationalized and harmonized way of damage stability that has become more and more feasible method since the development of computation in the current millennia. (Francescutto & Papanikolaou 2010)

Intact stability considerations were introduced for the first time in SOLAS in year 1974 as chapter 6 included regulation 4 "*Intact stability requirements*". The rules introduced requirements concerning grain shift, area under GZ curve and minimum GM value accounting free surface effect (IMCO 1974). However research on intact stability of ships was already on some parts on that level almost two decades earlier, as Rahola (1939) determined limits for minimum stability in his studies. The intact stability rules were later updated on 1991 to include also assessment of intact stability under high winds and parametric rolling (IMO MSC.22(59)). Major update on 2008 introduced a CODE ON INTACT STABILITY to summarize intact stability rules under one set of rules. It also introduced new optional requirements concerning effects of free surfaces, icing and watertight integrity (IMO 2008).

The new IMO (International Maritime Organization) regulation 'International code for ships operating in polar waters', or 'Polar Code' as used here after, aims to continue this evolution of safe ship design and operational safety before the worst happens. Increasing interest towards shorter passages between Europe and Asia, as well as Eastern parts of North America and Asia will rise the change of an accident at Polar waters. The cruise industry is also seeking new opportunities from expedition cruises more extensively as demand for this type of cruises is rising. The Polar Code guides how to consider the special climate conditions in ship design and safety measures. Possibly the most dominating features of these harsh areas are very cold temperature and remoteness of infrastructure. (Arctic council 2009)

As the number of ships designed for the operations in the arctic waters will likely increase in the future, safe design of ships is necessary (Ihalainen 2017). This safe design of ships is especially important for the safety of passenger ships where large number of people are onboard. Another big concern and reason for the new safety regulations in the Polar areas is the protection of the environment from all external substances that may end up in the water. Remoteness and cold climate makes cleaning of these areas from accidents very difficult. Previously there was no uniform rules or even any mandatory requirements for ship design and operations, as each country in the area had their own rules for navigation in ice covered seas. Canada, Russia and Baltic Sea area have relatively long traditions in shipbuilding and ship operations in ice covered waters, before Polar Code came in to force, nothing could have stopped for example some non-experienced shipbuilder to build a vessel for these areas with open water design. Even though such attempt would be irrational and the vessel would not necessarily not receive icebreaker assistance as quickly as an ice going vessel in areas with local ice rules. Sailing international ice infested waters with incapable ship would be even more irrational.

Polar Code aims to unify the rules so it is clearer to determine the requirements for ship design. A ship that fulfills the Polar Code requirements can have the Polar Ship Certificate to prove that the ship in question is capable for operations in the special and demanding environmental conditions of the polar waters. With this certificate, the ship's insurance is valid for to the environmental conditions described by the certificate, as Polar Code divides ships in to three categories depending the severity of possible ice conditions.

Modern ice-going ships are usually designed in respect to IACS (International Association of Classification Societies) polar class requirements to have certain polar - ice class. These classes define in how harsh ice conditions the ship can operate safely. The aim of these structural and equipment rules by IACS is that the ship will not confront severe structural damages in the ice conditions to which the ship has been designed. The IACS rules do not comment the situation where the damage happens, meaning that the values and equations in the IACS polar class requirements are explained in the rule text to give clear idea how the rules need to be implemented in ship design to assure that the ship will survive in the ice conditions it is designed. Figure 2 illustrates modern ice breaker Polaris, delivered in 2016 and built into Polar Class 4 (PC-4). Polaris has ice breaking capability to sail through at least 1.8 meters thick ice as designed. (FTA 2014)

Figure 2. Modern icebreaker Polaris, ice class PC-4 (Aker Arctic 2017).

The Polar Code is linked to the IACS polar class requirements in so that the IACS polar classes can be used to define into which category a ship will be included when interpreting the Polar Code. In Polar Code, ships are divided into three categories based on their intended operational area and capability. The category has effect on how the Polar Code is applied for a ship. For example, the damage stability requirements concern category A and B ships but not category C ships. The category of a ship is thus one key parameter dividing polar ships by their capability of navigation in polar waters. The operational area has big effect how likely ice related damages are. The risk is higher in colder areas where ice concentration is higher and encountering of multiyear ice is more likely. The cause for the accident can be for example human error or underestimation of the environmental circumstances. Unexpected multiyear ice or shallow water may lie in ships path because of uncharted waters and lack of reliable ice charts and accurate weather forecasts. (Arctic council 2009) Approximately only 10% of the Arctic have accurate navigational charts that have been produced with precision mapping methods such as continuous bottom profiling and vessel position recording with satellite positioning. (Canadian Coast Guard 2012) The satellite imaging is not capable of providing as highly detailed images of the sea and ice as it is in higher latitudes. The weather system/forecasting is also not as accurate as in more used sea and land areas since there is not that long experience and history of weather forecasting in these remote areas. (Orimolade et al. 2016)

Recent accident at the polar waters

Increasing interest and traffic at polar waters rises the risk of accidents at these areas.
1.2 Before year 2017 no international rule concerned specifically the special operational areas of Arctic and Antarctic waters, controlling what kind of vessels are allowed to navigate there. To highlight the importance of Polar Code and provide understanding about accident scenarios at these polar waters, two accident cases are introduced here. One concerning an old passenger ship navigating at Antarctic and the second case concerning a cargo vessel operating in the Arctic waters at Northwest Passage.

1.2.1 Sinking of the MV Explorer, 2007

In 2007 passenger vessel Explorer, built in 1969 to 1A1 ICE-A class, sank in the Antarctic waters after a collision with ice ridge. The main reason for the accident was captain's wrong estimation about the ice conditions, as he thought it was first year ice, but in reality, there was also hard land ice among the first year ice. Another reason for sinking, after the impact with ice ridge had made approximately 3.1m long breach to the hull, was that a watertight door between compartments leaked and allowed the water to gradually flood into two watertight compartments. The ship was designed to survive only one-compartment damages as the rules required at the time (LBMA 2009). The ship had history of over 250 Antarctic voyages, which displays that the Explorer was in some level suitable for operations in polar waters. (LBMA 2009)

The Explorer's damage case is interesting especially from the ice class and ship's capabilities point-of-view. The ship was built in 1969 according to DNV 1A1 ICE-A class rules and it retained that class through its service as the classification regulations allowed to remain the old ice class notation, even though the requirements for ice going ships renewed and higher standards were introduced. (LBMA 2009) (DNV 2011) In this case, one main requirement that has been renewed in the classification system regarding ice strengthening from the 1969, is the determination of adequate plate thickness. The shell plate thickness in Explorer was 13 mm in the whole hull which was one millimeter more than the minimum thickness of 12 mm required for 1A1 ICE-A class. In addition, the hull of Explorer was single hull design. At that time the thickness of plates and scantlings was determined as a percentage increase from normal open water class rules in the Explorer and other ships prior to year 1971, as the approach of design ice loads was not yet introduced as a class rule. To give some perspective, for example Finnish-Swedish ice rules would require at least 18.8 mm plate thickness in the bow-area for the Explorer if it would be built in 2017 to lowest 1C Finnish-Swedish ice class. (Trafi 2010a) The plate thickness calculation is carried out with 0.5 meter transversal frame spacing to obtain the result of 18.8 mm.

The case of Explorer displays very well two things. Firstly, even if the design is done at the time of construction according to best current knowledge, it may not be sufficient in reality for its purpose as the time passes and operational areas change. Secondly, human errors are hard to avoid as the sea conditions in certain areas vary greatly from year to year and even in the matter of hours. To overcome these problems related to estimation of ice conditions, faster and more reliable information of ice conditions needs to be available for ships at sea. (Arctic council 2009)

Figure 3. MV Explorer sinking at Antarctic water in 2007. (Wikiedia/Jahn, R 2007)

1.2.2 Sinking of the MS Finnpolaris, 1991

MS Finnpolaris, built to ice class 1A (in accordance to FSICR), sank on 11.08.1991 nearby Disco bay at the coast of Greenland. (OTKES 2002) Finnpolaris was carrying zinc-ore as it sailed through a seaway that was ice infested with floes. The weather at the time of the incident was foggy with approximately maximum of 7-8 m/s winds and 5 m high waves. Suddenly a wave slammed a bergy-bit -sized piece of ice to the starboard side hull and captain reported the ship started to heel very rapidly. The bergy-bit punctured the hull so that the cargo hold flooded and water mixed with zinc-ore. Due to the heeling of the ship, the portside lifeboat was not possible to be used, leavign only one of the two lifeboats usable. 15 hours from the ice impact, the Finnpolaris was completely sank. All crew was rescued approximately 7 hours after the accident, as oil tanker Sofie Teresa was closest to the scene of the accident. The rescue time was quite critical aspect in this accident case because the life boat the crew used was open-top model, so the crew was in directly exposed to the weather. At the time of the rescue, some of the crew members were already so exhausted that they could not climb onboard of the rescue vessel with their own strength. (High Seas Rescue 2000). Figure 4 illustrates the sea and weather conditions after the collision with ice.

The rescue operation of the crew was supported by the Canadian coast guard as their aircraft was already in the air and in the range when the M/S Finnpolaris sent distress call. The coordinates and navigational aid from the aircraft gave the oil tanker Sofie Teresa important information where to take course. As the captain of the MT Sofie Teresa explains in the document (High Seas Rescue 2000), it is very difficult to estimate the best route in ice, only with the observations made from the bridge of the ship.

Figure 4. MS Finnpolaris sinking (High Seas Rescue 2000).

1.3 *Polar Code in general*

The new Polar Code has come into effect on 01.01.2017. Its purpose is to give instructions and guidance for ship operations and safe ship design for vessels that are intended to operate in the waters near the polar areas. All of the Polar Code regulations will be valid for ships that are constructed after the Polar Code has become into effect. It is intended to supplement the existing IACS polar class system that considers in more detail the structural requirements, and is aimed solely for ship designers. Polar Code's purpose is to give more general view of the environment and safety risks that need to be taken into account in ship design and when operating in the Polar Regions. Its requirements and aspects are also provided for the crew onboard. (Polar Code)

Polar Code defines three different ship categories dividing polar ships by their intended operational ice conditions. It is worth noticing that Polar Code does not have requirements for ice braking capability, but determination of the categories is linked to ice classes. The different categories are presented below as described in the Polar Code (IMO 2015a):

- Category A ship means a ship designed for operation in polar waters in at least medium first-year ice, which may include old ice inclusions.

- Category B ship means a ship not included in category A, designed for operation in polar waters in at least thin first-year ice, which may include old ice inclusions.

- Category C ship means a ship designed to operate in open water or in ice conditions less severe than those included in categories A and B.

The IACS polar ice class system can describe the category A and B ships by the use of steel grade and amount used in the structures. Category A ship's structures need to follow the requirements intended for IACS polar classes 1-5 and category B ships polar classes 6-7. For category C ships the Polar Code states (IMO 2015a):

"*…scantlings of ice strengthened category C ships shall be approved by the Administration, or a recognized organization accepted by it, taking into account acceptable standards adequate for the ice types and concentrations encountered in the area of operation; and a category C ship need not be ice strengthened if, in the opinion of the Administration, the ship's structure is adequate for its intended operation.*"

This leaves more possibilities for interpretation in the design of category C ships, which may include pure open water ships or ships with ice class lower than IACS polar class 7. These lower classes can be for example FSICR 1B and 1C ice classes which are capable to operate in medium to easy ice condition at Baltic Sea, meaning 0.6 and 0.4 meters of sea ice. However also these classes are vulnerable for multiyear ice, as the recent accident cases proved that even higher ice classes may sink due to impact on such hard ice.

The ship categories give also more indication how Polar Code is linked to the IACS polar ice class system that was adopted 1st of July in 2007 to divide ships according to the capability how thick ice the hull can withstand and break as the ship is moving in the ice. This can be seen also as a reason for ship owners to build their vessels according to IACS ice class rules so that comparison of vessels is more straightforward than with ships that follow local ice rules or some other design requirements. Another reason for the use of IACS ice class rules is that having a common way of ship design, the resale value of the vessel is potentially higher since it is easier for other ship owners to assess the ship's capabilities with the common reference system.

The Polar Code is divided into two main parts: A and B. The part A includes all mandatory regulations and part B includes the recommendatory provisions to extend part A. Both A and B are sub-divided into sections I and II. Part I focuses on requirements for safe design of the ship and safety equipment onboard. The part II focuses on pollution prevention.

The contents of the Polar Code is aimed to increase the maritime safety in the harsh and environmentally delegate polar waters. (IMO 2015a) The polar waters in question are defined as in SOLAS regulations XIV/1.2 and XIV/1.3 and also by MARPOL Annex I, regulations 1.11.7 and 46.2; Annex II, regulations 13.8.1 and 21.2; Annex IV, regulations 17.2 and 17.3; and Annex V, regulations 1.14.7 and 13.2 (IMO 2014) (IMO 2015b. The areas of polar waters in question are illustrated in Figure 5 and Figure 6 below. Ships operating in these areas must follow the requirements of the Polar Code, however the areas in the charts are for illustrative purposes only and the final estimation of sea conditions is on the responsibility of ship captain.

Figure 5. Area of Arctic waters in northern hemisphere. (IMO 2015a)

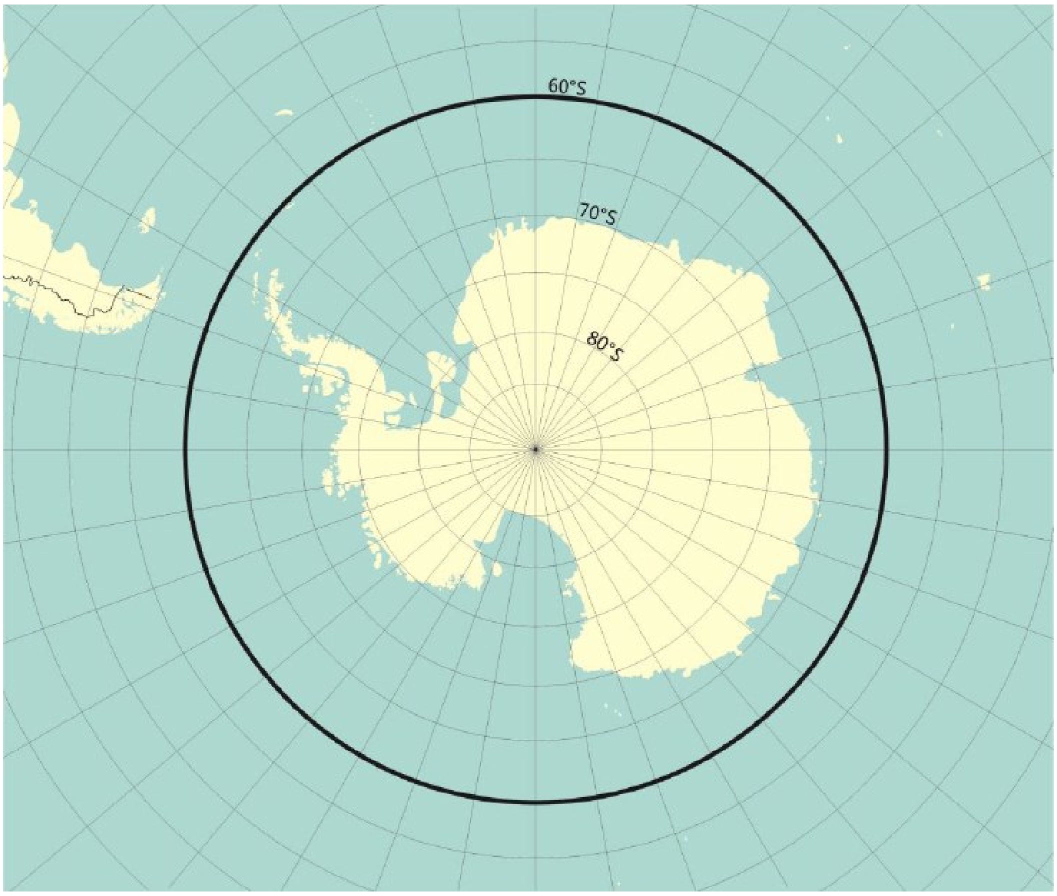

Figure 6. Area of Antarctic waters in southern hemisphere. (IMO 2015a)

Polar Code gives also instructions on various areas of ship design and operations. These topics include ship structures, subdivision and stability, water and weather tight integrity, machinery, fire safety, life-saving systems such as life boats, safety of navigation and communication, voyage planning and crew duties on board and crew training. These cover all the aspects that can be affected by cold the climate and remoteness to infrastructure. Polar Code's chapter 4, concerning subdivision and stability, includes the stability requirements for damage and intact stability scenarios. These rules states the measures for the damage length, height and penetration and icing allowances for intact stability part.

With the damage dimensions, all relevant damage cases are identified. These damage cases has to cover all different combinations of compartments that can be flooded based on the location of the damage. Damage length and height are obtained as a certain percentage of ships particulars. The penetration of the damage is a fixed value for all sized ships, being 0.76 meters. It is worth of noticing already here that the Polar Code does not state that smaller damage cases should be studied. In addition, Polar Code does not state weather simultaneous icing and ice-related damage should be studied.

The intact stability part of the Polar Code takes into account the accumulation of ice on the ship's exposed external structures. The amount of accumulated ice is determined by the vertical and lateral areas of exposed superstructure. The rule sets certain mass-per-area value for these exposed ship structures and guides that ships should be designed so that icing of the structures is minimized.

1.4 *Scope of the study*

The purpose of this thesis is to study the stability chapter, *CHAPTER 4 –SUBDIVISION AND STABILITY*, of the Polar Code in terms of intact and damage stability. The goal related to damage stability is to create new NAPA software tool to identify the relevant damage cases and analyze the effects of these damage scenarios on ship stability with an example ship model as a case study. The goal for the intact stability part of the Polar Code, is to create a NAPA software tool to account the icing on the lateral and horizontal ship structures. With the help of this tool it is possible to implement the effect of added mass due to icing for intact stability calculations and analyze the effects on ship stability with example ship models.

Main objective of these tools is to be accurate and efficient to identify and represent the conditions to be studied. The secondary objective is to make these tools to be as universal as possible so that they are efficient to use with all shaped ships. With these tools, it is possible to study how Polar Code's stability requirements affects the design of new vessels and how the requirements have effect on existing ships that are originally intended or converted for operations in polar waters, but not designed directly as per Polar Code.

The purpose of developed tools is naturally also provide more efficient way for stability calculations in respect of time and reliability.

One part of the study is to determine appropriate ship(s) to carry out the case studies. For damage stability example calculations it is important to acquire a realistic ship model that is designed to fulfill relevant rules, so that the results can be seen to reflect realistic scenarios. For intact stability case studies less realistic ship models are adequate, as only hull form and loading conditions have influence on results. What is also important is to consider how in general the Polar Code affects those existing ships that area already operating in polar areas or will be converted for polar operations. One aim of stability tools development is that they should work with conventional hull forms.

The analysis part of the thesis will study how the damage scenarios and icing affects the stability of selected example ships. Major part of the thesis is to develop and offer an efficient way for damage generation and filtering and also for the ice accumulation on the ship's external structures.

This thesis is not aimed to provide optimum design solutions or practices for arctic ship design. Also the parts of Polar Code that are not focused to ship stability are considered only on general level to provide more complete understanding of the Polar Code as whole. Also both, intact and damage stability, tools to be offered are developed and studied with conventional hull and superstructure forms, and the cases of more complex or special ships are not covered in order to keep the focus of the study limited. The aim of the developed tools is not to do everything ready for the designer but to help to create the required intact and damage stability scenarios, reducing the amount of manual work.

The methods for carrying out the study are firstly literature review, to see what has been done in the past and what has been the driver in the development of the rules and regulation regarding the ship stability and operations in the ice covered seas. Second method in the thesis is to experimentally study ship stability as stated in the Polar Code for intact and damage conditions. The experimental part is carried out by NAPA software, which currently does not have ready built support or tools for these purposes of accounting icing and finding relevant damage cases as Polar Code defines them. Thus one important step in the experimental study is to develop tools to account the icing and filtering out the relevant damage cases that fulfill the Polar Code damage extents. The tool for icing uses the 3D ship model to obtain deck areas and lateral projection of the ship to determine the amount of ice accumulation, to be then used as a mass load in desired loading condition. The damage stability related tool is aimed to use several filters to find all relevant cases out of all damage scenarios that NAPA can automatically create, based on ships subdivision. These tools must be developed first in order to obtain the results how the stability rules affect ship stability.

2 Review of the Polar code

The four main factors and guidelines affecting polar-ship design and operations are: SOLAS, MARPOL, classification societies and the governmental ice rules. Governmental rules may concern more special aspects of ship design, such as winter navigation. These set the limits in which the ship designers can use their own expertise and vision for the ship design. The national and international rules for ship design and building exist to ensure the safety of shipping and setting all flag states to same line on safety standards.

The governmental rules for winter navigation mean that in some special sea areas local officials have set their own design principles for the design and construction of ice going ships. These rules usually define the ice class of the vessel and the aim of the local rules is to encourage ship owners to have safer and more capable ships in these special areas so that accidents would not happen and ships could navigate more independently. For example at northern Baltic Sea area, ship with a higher ice class will have lower fairway dues and better access for icebreaker assistance when needed according to FSICR (Finnish-Swedish ice class rules) (Kujala & Riska 2010) (Trafi 2010a).

However, as the polar waters are in some areas international waters or icebreaker assistance is not available, the aim of the Polar Code is to guide the ship design and operations so that all vessels navigating in these areas are capable to withstand and survive independently in rough sea and weather conditions for which the ship is designed. The aim of the Polar Code can be divided firstly to accident prevention by ship design and risk assessment, and secondly to ensure ship and crew safety in case of accident. Third goal of the Polar Code is protection of arctic environment. In the scope of ship stability, these aspects are represented in the Polar Code by rules concerning ship's intact and damage stability.

The Polar Code regulations are additional safety precautions for ships operating in polar waters that are considered as an addition for the existing regulations. In other words, all the previous and existing regulations need to be taken into account as in the past, and by
2.1 those parts where Polar Code sets higher safety and design requirements, the Polar Code is applied.

Effects on new ships

Polar Code sets five new safety measures in part I-A which is mandatory for the new-builds that are started on or after 01.01.2017. Naturally, new-builds must be in accordance with other requirements in Polar Code also. These new-build specific requirements are focused on the special environment where safety of people and function of equipment need to be taken account differently, compared to ships sailing in warmer sea areas and closer to infrastructure. These requirements concerning only new-builds are (IMO 2015a):

1. The damage stability requirement as in PC section 4.3.2.
2. For ships constructed on or after 1 January 2017, exposed escape routes shall be arranged so as not to hinder passage by persons wearing suitable polar clothing, as stated in PC 8.3.1.2 section.
3. Ships constructed on or after 1 January 2017, ice strengthened in accordance with chapter 3, shall have either two independent echo-sounding devices or one echo-sounding device with two separate independent transducers, as stated in PC 9.3.2.1.1 section.
4. In category A and B ships constructed on or after 1 January 2017, the bridge wings shall be enclosed or designed to protect navigational equipment and operating personnel, as stated in PC 9.3.2.1.4.2 section.

In addition to this Polar Code gives also recommendations for these new-builds about pollution prevention in part II-A. Pollution prevention is also linked to the ship's structural design and thus it can be in some cases difficult to convert old ships to correspond new regulations, however most of the regulations concerning structural design are mandatory for new-builds only. The pollution prevention requirements for new-builds are presented in six sections of Polar Code. These pollution prevention requirements are (IMO 2015a):

5. For category A and B ships constructed on or after 1 January 2017 with an aggregate oil fuel capacity of less than 600 m^3, all oil fuel tanks shall be separated from the outer shell by a distance of not less than 0.76 m. This provision does not apply to small oil fuel tanks with a maximum individual capacity not greater than 30 m^3.
6. For category A and B ships other than oil tankers constructed on or after 1 January 2017, all cargo tanks constructed and utilized to carry oil shall be separated from the outer shell by a distance of not less than 0.76 m.
7. For category A and B oil tankers of less than 5,000 tonnes deadweight constructed on or after 1 January 2017, the entire cargo tank length shall be protected with:
    a. double bottom tanks or spaces complying with the applicable requirements of regulation 19.6.1 of MARPOL Annex I; and
    b. wing tanks or spaces arranged in accordance with regulation 19.3.1 of MARPOL Annex I and complying with the applicable requirements for distance referred to in regulation 19.6.2 of MARPOL Annex I.
8. For category A and B ships constructed on or after 1 January 2017 all oil residue (sludge) tanks and oily bilge water holding tanks shall be

separated from the outer shell by a distance of not less than 0.76 m. This provision does not apply to small tanks with a maximum individual capacity not greater than 30 m^3.

9. For category A and B ships constructed on or after 1 January 2017, the carriage of NLS identified in chapter 17, column e, as ship type 3 or identified as NLS in chapter 18 of the International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk in cargo tanks of type 3 ships shall be subject to the approval of the Administration. The results shall be reflected on the International Pollution Prevention Certificate for the Carriage of Noxious Liquid Substances in Bulk or Certificate of Fitness identifying the operation in polar waters.
10. Discharge of sewage into the sea is prohibited from category A and B ships constructed on or after 1 January 2017 and all passenger ships constructed on or after 1 January 2017, except when such discharges are in compliance with paragraph 4.2.1.3 of this chapter.

If a new ship is not designed according to Polar Code, but later in the future it is re-routed to operate in the polar waters, it needs to fulfill the Polar Code criteria to obtain the polar ship certificate. In this case, damage stability requirement may pose a difficult challenge. Especially for passenger vessels, offshore supply vessels and bulk carriers this can lead to a re-design and modification of subdivision after SOLAS requirements has been followed in the original design, according to American Bureau of Shipping (ABS 2016). This is because SOLAS requires the probabilistic damage stability approach, which leaves possibility for damage that will sink the ship under damage scenario described in Polar Code. According to ABS (2016) tankers are the only ship type that already is required to fulfill two-compartment damage requirements with even larger transverse extent as defined in Polar Code.

2.2 *Effects on existing ships*

Polar Code affects also existing ships that are already operating, or will be converted for polar water operations. In practice, this means that ship owner needs to prove that all requirements mentioned in Polar Code are fulfilled, apart from those that are specified to concern only the new-builds. The hull structure is one of the key factors affecting directly into which category the ship will be included by the Polar Code. For stability point-of-view, the effect of ice accumulation on intact stability needs to be studied for existing ships. However the damage stability requirement concerns only new-builds. The Polar Code mandatory rules apply to all existing ships, apart from the 10 requirements for new-builds only, mentioned in the earlier chapter 2.1.

The most remarkable effect for existing ships is that they need to prove their polar worthiness, which means that the ship needs to have adequate ice class depending on its planned operational area. In addition requirements on watertight and weather tight integrity, machinery installations, fire safety/protection, life-saving appliances and arrangements, safety of navigation, communication and voyage planning needs to be taken into account. These aspects are taken into account by considering the possible effects of coldness, wind, rain and remoteness.

One of the most severe effects is icing which may prevent the use of doors and hatches, navigational and communication devices. Also the geographical position set requirements for navigational equipment because of declination and uncharted seabed. For these reasons sufficient sounding devices and navigational equipment is needed. (IMO 2015a) In addition, navigational GPS devices have been detected to have some problems in high latitudes related to weak vertical signal of GPS since there is no satellites directly above and some issues in GPS log-files when transiting over the International Date Line making the location data incorrect (Salokannel 2013) (ABS 2016). Icing is also a concern for ship stability as it accumulates on ship increasing the displacement and center of gravity.

2.3 *Differences between category A, B and C ships*

As mentioned in earlier chapters, Polar Code divides ships into three categories. The purpose of the categories is to set thresholds for operational areas acceptable for ships depending on their capability to survive in different ice conditions in remote areas. The main parameter for defining into which Polar Code -category an existing ship should be included, is the IACS Polar Class structural requirements. If ship is built according to some other ice class requirements, then a comparison carried out to determine which IACS polar class resembles it closest.

The comparison is especially important when ship's ice class is low, when possible Polar Code categories for such vessel are respectively B or C. To ease this comparison, Trafi (2010b) has prepared a table to compare other ice class rules to FSICR. Based on Trafi's data, Table 1 is gathered to compare different ice classes in respect IACS ice classes PC 6 and PC 7. The operational areas are defined according to current weather and sea conditions, and the operational area charts in Figure 5 and Figure 6 as mentioned earlier, are only for illustrative purposes. The final responsibility of evaluating the current sea and ice conditions, and whether or not those conditions area inside the limits described in the ships Polar Class Certificate, is in the hands of the master of the ship (IMO 2015a).

Table 1. Equivalent ice classes for PC 6 and PC 7, comparable Polar Code category B (Trafi 2010b).

Classification society or Authority	**PC 6 corresponding ice class**	**PC 7 corresponding ice class**
ABS	Ice Class I AA	Ice Class I A
BV	Ice Class IA Super	Ice Class IA
CCS	Ice class B1*	Ice class B1
DNV	ICE-1A*	ICE-1A
FSICR	IA Super	IA
GL	E4	E3
KRS	IA Super	IA
LR	100 A1 Ice Class 1AS FS	100 A1 Ice Class 1A FS
NKK	NS (Class IA Super Ice Strengthening)	NS (Class IA Ice Strengthening)
PRS	L1A	L1
RINA	ICE CLASS IA SUPER	ICE CLASS IA
RMRS	Arc 5 – Arc 7	Arc 4

Division to categories A and B is straight forward when ship is built directly according to IACS Polar Class rules. Polar classes PC 1-5 are included in category A, and classes PC-6 and PC-7 are included to category B. (IMO 2015a) Requirements for category C ships have more room for interpretation, depending on expected ice condition in designed operational area. Approval of hull structures for category C ships is thus relying more on co-operation with relevant administration since these cases have more individual and distinctive nature in respect to operational conditions.

Biggest difference in operational area and requirement perspective is between category C and category B ships. Category C ships are allowed to sail only in such sea conditions where no ice is present or ice condition are less severe than for category A and B ships, and thus the damage stability requirement is not mandatory as ice conditions are nonexistent or easy. In addition for category C ships ice strengthening is not directly mandatory, when according to the Administration's opinion the current structure of the hull is adequate for the ships purpose and operational area. (IMO 2015a)

It is expected that many of the passenger vessels designed for cruises in polar waters will be designed into category C (Ihalainen 2017). The damage stability requirement would not then be mandatory for passenger ships in category C, even though, according to

American Bureau of Shipping (ABS 2016) there had been concerns in the Polar Code development group about the safety of category C vessels in case of ice related damage.

Background to stability requirements

2.4.1 Intact stability

2.4 In areas where temperature can go below freezing point, ice can start to form on ship's external structures. In the past. In the Polar Code, this is taken into consideration by taking account icing on vertical and lateral structures. Same stability requirements are also introduced earlier in the IMO IS 2008 -code (IMO 2008) where these optional requirements are intended for those ships expected to operate in areas where icing is likely to occur. Ice accretion requirements have been also introduced already in 1993 in fishing vessel guidelines (Torremolinos Protocol 1993).

All ships that are intended to have the Polar Ship Certificate (Polar Code), are required be designed according to the intact stability requirements of the Polar Code. The rule for intact stability concerns all vessels, new and existing, that are intended to have polar ship certificate and if the ship is subjected to ice accretion in its planned operations. The intact stability rule states (IMO 2015a):

1. 30 kg/m^2 on exposed weather decks and gangways;
2. 7.5 kg/m^2 for the projected lateral area of each side of the ship above the water plane; and
3. the projected lateral area of discontinuous surfaces of rail, sundry booms, spars (except masts) and rigging of ships having no sails and the projected lateral area of other small objects shall be computed by increasing the total projected area of continuous surfaces by 5% and the static moments of this area by 10%.

The above-mentioned icing allowance has to be taken into account in the stability calculations that are relevant for the ship. The icing affects ship stability by increasing the center of gravity and thus making the ship more unstable by decreasing the GM value and increasing rolling moment (ABS 2016). To ease the designing of vessels and intact stability calculation, a tool is developed in this study to calculate the effect of ice accumulation on ship's external structures. The main idea of the tool is to calculate ship's external lateral and exposed deck areas where ice can accumulate.

It is worth highlighting that the icing allowance is not needed to be taken into account if the ship is not subjected to ice accretion. The assessment whether or not the icing allowance is relevant for specific ship is not clarified in the Polar Code. The possibility of the relevance of icing is considered in the Operation Assessment part of the Polar Code. Ship's intended operational area and seasonal variation in weather condition are two important factors in this assessment (Lloyd's Register 2016). The chart of areas of having high possibility for icing in Figure 7, gives some advice on the matter, but does not differentiate seasonal changes in the areas.

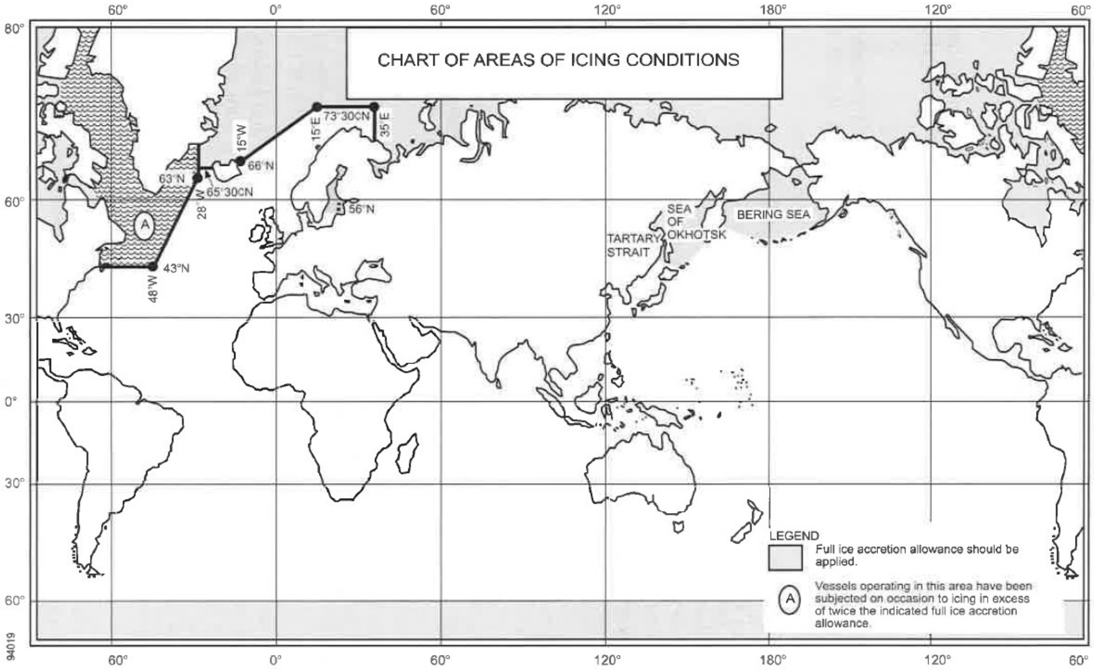

Figure 7. Chart of areas of icing conditions (IMO 2008)

The weather conditions for icing are most severe when temperature is below freezing point and high winds and waves are present, combined with rain in liquid or snow form. Ice accretion can be originate from two sources of water; from seawater-spray icing or atmospheric icing. Especially such sea conditions where wavelength and amplitude that makes the ship bow ram into the next wave causes water to spray in the air. In a study by Borisenkov and Panov (1972), it was observed from around 3000 cases of icing on ships, that the seawater spray is the main source of icing with 89% portion of all icing causes. In the arctic seas, approximately 50% of icing cases has been caused only from seawater spray and 41% of cases are a combination of seawater spray and atmospheric icing (Makkonen 1984). According to Makkonen’s (1984) study much smaller portion of icing cases are caused by only atmospheric icing, where 6% is due to rain and 3% because of fog alone.

Ice accumulation can be expected to occur up to the height of 15 m from the sea level, after which seawater spray is insignificant source of icing (Minsk 1977). In seawater spray icing, wind is naturally an important factor, conveying the water in the air over the ship. For structures above the 15-meter limit, atmospheric icing becomes more likely source of icing and therefore these higher parts of superstructure are reasonable to be taken into account in intact stability calculations. However, in favorable conditions it has been recorded seawater spray related icing to occur at heights of 30 meter over the water line on fast passenger ship, GTS Finnjet, where high speed was noticed to be one factor resulting spray icing to reach higher decks (Makkonen 1984).

Figure 8. Icing on ship (Wikimedia/Robert A. Pawlowski)

The icing allowances set in the Polar Code give design values for the ice accumulation per deck area. It is a simple approach to calculate the total mass and center of gravity for the accumulated ice masses. The icing allowances of 30 kg/m^2 for horizontal areas and 7.5 kg/m^2 for lateral projection results ice layer thickness of 3.28 cm for deck areas and 0.82 cm for lateral projection, using value 915 kg/m^3 for ice density. These values are in a range of icing values that can be expected after ship has been around one to three hours in a polar low situation, which is a weather phenomenon in the Norwegian and Barents seas that involve high winds, waves and raining or snowfalls, due to fast-moving cold air front (Orimolade et al. 2016). In the study by Orimolande et al. (2016) three different icing rates of 1.47, 0.45, and 2.05 cm/h were obtained from three separate polar low situation in the Barents Sea, reviling that especially low temperature is key factor for rapid ice accretion.

One extreme icing event that has been recorded took place on February 1987 for a 105 meter-long Norwegian coast guard vessel KV Nordkapp, sailing from Tromsø towards Svalbard in the border of Norwegian and Barents seas. In this icing case, approximately

20 cm thick layer of ice was measured on the fore part of the main deck after 17 hours of polar low weather, resulting total of 110 tons of ice (Samuelsen et al. 2015). The temperature in this case varied between $-10°C$ to $-20°C$, winds blowing at 20-30 m/s and waves reaching 7.5 meters high. Despite the extreme icing, KV Nordkapp remained its stability. This extremely high ice accretion value is also used in some cases as a design value for ice going ships. Use of higher ice accretion values have support from Hovilainen and Vocke (2017) who state that approximately 10 times higher ice accretion values, compared to ones in the Polar Code, have been used in the past when designing certain ice-going vessels due to classification society requirement. These ice accretion values would mean ice thickness to be in range of 30 cm for deck areas and around 8 cm for lateral areas.

Wires and cables are especially prone for icing, for which reason Polar Code guides to design ships in a way to minimize icing. In 1920 observations from Soviet Union, recorded icing of 11.4 cm in diameter was accumulated on a 5 mm thick wire (Minsk 1980). Another high icing incident recorded occurred in Canada, Newfoundland, where 25 cm diameter icing was measured on the guy-wires of radio tower (Boyd and Williams 1968).

Icing is a serious threat for ships navigating in polar waters. Weather forecasts for icing are part of the information that different meteorological organizations offer for seafarers. Icing is especially threat for smaller vessels such as fishing vessels since the icing has relatively larger effect on their stability because of lower freeboard and more surfaces like masts and wires for ice to accrete, in comparison to vessel size (Kobylinski 2015). Icing occurs relatively often at polar waters as there has been over 1200 recorded icing events between 1970-2005 in the eastern coast of Canada (Timco & Kubat 2005). The icing incident reports until 1985 know 26 cases when ship sank due to icing, out of about 300 recorded cases of icing incidents, so at least in the past icing has caused many accidents (Kobylinski 2015). Especially smaller ships such as trawlers and coast guard vessels are found to be most vulnerable for icing (Kobylinski 2015) (Kozo 1986).

2.4.2 Damage stability

Damage stability regulation in Polar Code consists about deterministic damage scenario. It is described with a 'damage-box' with certain extents depending of the ships dimensions. The purpose of the damage scenario in the Polar Code is to take into account special cases of ice related damages that is unique for polar waters. The ice related damages occur mostly due to hard multiyear ice (Kubat & Timco 2003).

In the study by Kubat and Timco, analyzing the damage data of 125 ice-related damage events in Canadian arctic, 73% of the cases were caused by multiyear ice. In three of these occasions the ship was sank. The data also shows that first year ice did not cause any loss of ship. In 19 cases of multiyear ice damage data, the ice has caused a large and significant hole to the hull but not total loss of vessel. The ice damage data in Kubat's and Timco's study (2003) has been gathered from accident reports between the years 1978-2003. Figure 9 shows the locations where these ice related damages have occurred according to a five-year earlier study by Timco & Morin (1998). The study reveals that approximately 12% of all over 1000 voyages recorded in the Canadian arctic are associated with a damage event, varying from shell plate and frame buckling until total loss of ship. However, some precaution is needed when reading the Figure 9 since it is strange that no damage cases have been recorded in the Northern Sea Route. The green 'no damage' legend in the map stands for safe transit trough ice infested sea area, and the red legends mark the location where ice related damage has taken place.

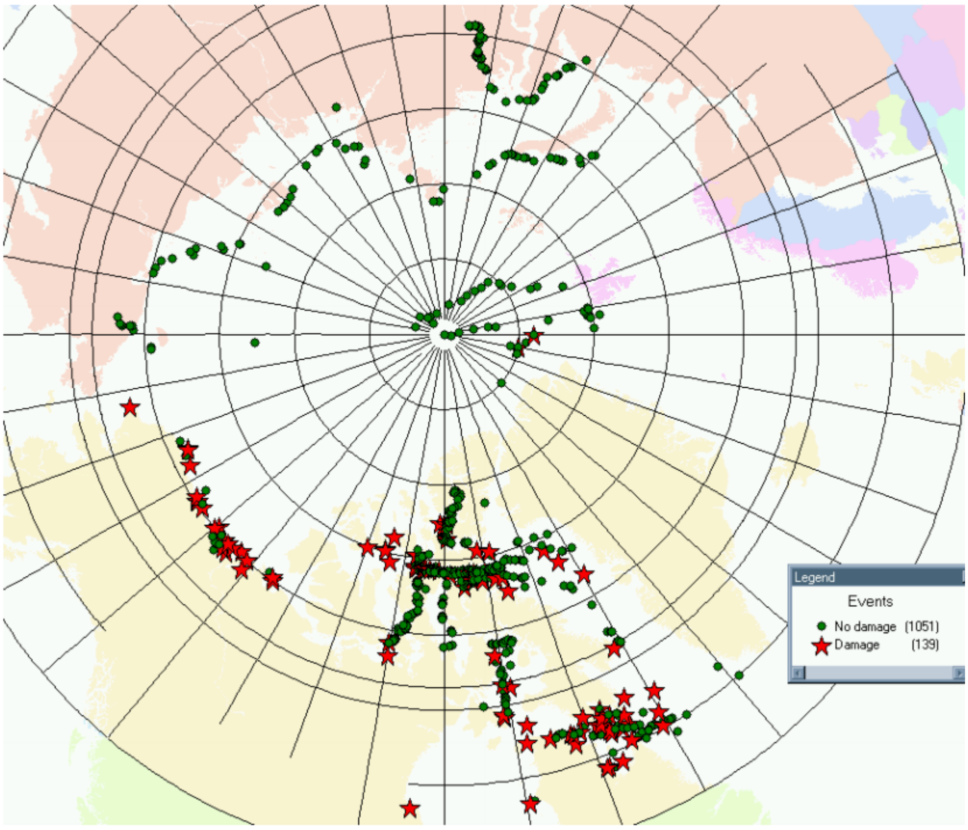

Figure 9. Location of ice related damages in Canadian arctic (Timco & Morin 1998).

The damage stability rules in Polar Code start with a statement about which ships the rule concerns, which are the new-build ships of categories A and B, but mentions also exception. It states for new-build cargo ships as follows (IMO 2015a):

However, for cargo ships that comply with subdivision and damage stability regulations in another instrument developed by the Organization, as provided by SOLAS regulation II-1/4.1, the residual stability criteria of that instrument shall be met for each loading condition.

This means that in some cases regulation may be stricter for example tankers and gas carriers and these cases also those regulation need to be considered.

The criteria for damage stability in Polar Code is set by using the survivability factor as used in SOLAS 2009 stability calculation for attained index determination. Polar Code requires that in every relevant damage scenario that the factor s=1. The intermediate stages of flooding are not taken into account in the calculation. Calculation of the factor s is presented by it parameters in equation below.

$$s_{final} = K * \left[\frac{GZ_{max}}{0.12} * \frac{Range}{16}\right]^{1/4}$$

Where GZ_{max} is the maximum positive righting lever, in meters, up to the angle θ_v, Range is the range of positive righting levers, in degrees, measured from the angle θ_e. The positive range is to be taken up to the angle θ_v, θ_v is the angle, in any stage of flooding, where the righting lever becomes negative, or the angle at which an opening incapable of being closed weathertight becomes submerged and K is obtained as,

K	for cargo ships
1	$\theta_e \leq 25°$
$\left(\frac{30-\theta_e}{5}\right)^{1/2}$	$25 < \theta_e < 30°$
0	$\theta_e \geq 30°$

K	for passenger ships
1	$\theta_e \leq 7°$
$\left(\frac{15-\theta_e}{8}\right)^{1/2}$	$7 < \theta_e < 15°$
0	$\theta_e \geq 15°$

In Polar Code's damage stability regulation, the damage length and height dimensions are in relation to ship's dimensions. It means that ice can cause larger size damages on larger vessels. The worst situation is that the ship will collide to a very large piece or flow of multi-year ice. In this kind of situation, the ice will not move very much and it will make the ship stop. Assuming the ship structures and ice-class are similar with larger and smaller vessel, the difference with larger vessel is that it has more mass and hence more kinetic energy for the ice floe to work against and stop the ship. This means that the ice or ship structures need to absorb the energy, and in the worst case, it is the ship structures deforming more as the ship size grows.

The assumed reason why Polar Code defines the damage extents as a percentage of vessel dimensions is assumed here to be the kinetic energy explanation, since no confirmed explanation was to be found after querying from several experts of the field. The Polar Code states the damage dimensions and damage locations to be studied as below (IMO 2015a):

1. The longitudinal extent is 4.5% of the upper ice waterline length if centred forward of the maximum breadth on the upper ice waterline, and 1.5% of upper ice waterline length otherwise, and shall be assumed at any longitudinal position along the ship's length;

2. The transverse penetration extent is 760 mm, measured normal to the shell over the full extent of the damage; and

3. The vertical extent is the lesser of 20% of the upper ice waterline draught or the longitudinal extent, and shall be assumed at any vertical position between the keel and 120% of the upper ice waterline draught.

The rule statements are short and easy to understand, but there lies few issues related interpretation. Firstly, in which direction vertical extent is measured in the bottom area of hull? Another interpretation issue concerns the longitudinal extent at bow and aft areas where hull has curvature. Is the longitudinal extent measured directly in respect to the X-axis from hull's shell plating, or is it measured from the inner parts of the damage-box, taking account the curvature and damage penetration in respect to the normal of the hull?

Since the section 1 in the rule discusses about the waterline length, it would be possible to understand that the damage length is applied also to the hull as looking directly the projection curve of the waterline in XZ -plane, as is the waterline length also measured. On other point of view, section 2 states that the transverse penetration must be measured to the normal direction of the hull. This indicates that damage length and vertical height, must be applied so that those extents are measured along the hull surface that may have curvature. The two possible interpretations are illustrated in below

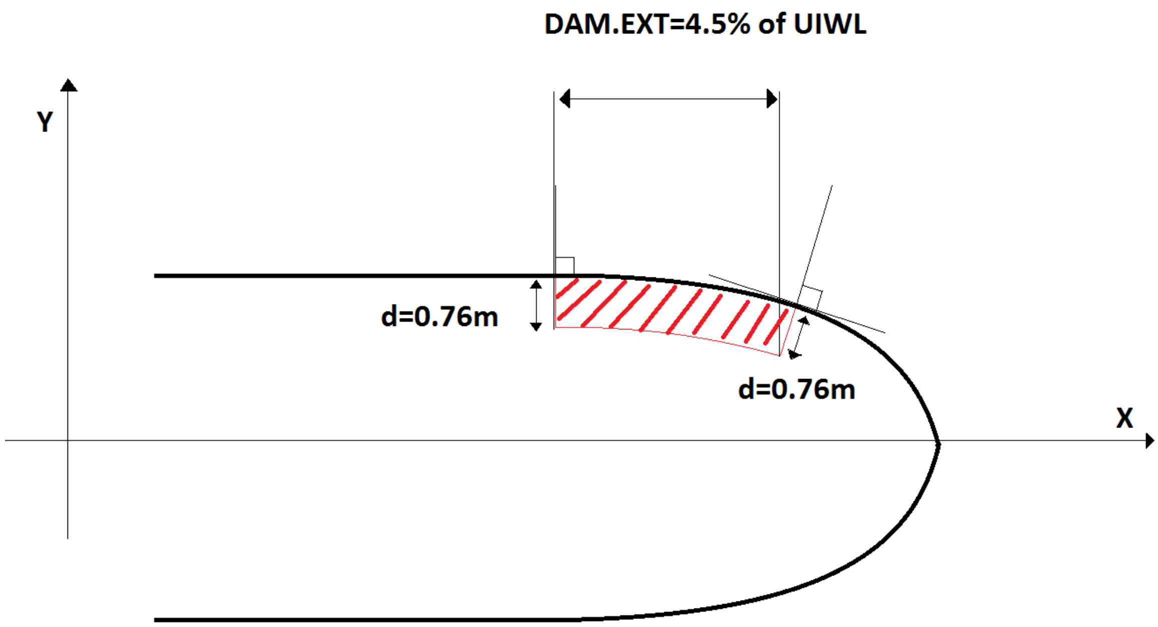

Figure 10 and Figure 11. In the figures, UIWL stands for upper ice waterline length.

Coordinate system used in the whole study is right-handed, where Z-axis get higher positive values when moving from keel line to the direction of main deck. Location of the origin is set to be at the intersection of the keel line and the aft perpendicular.

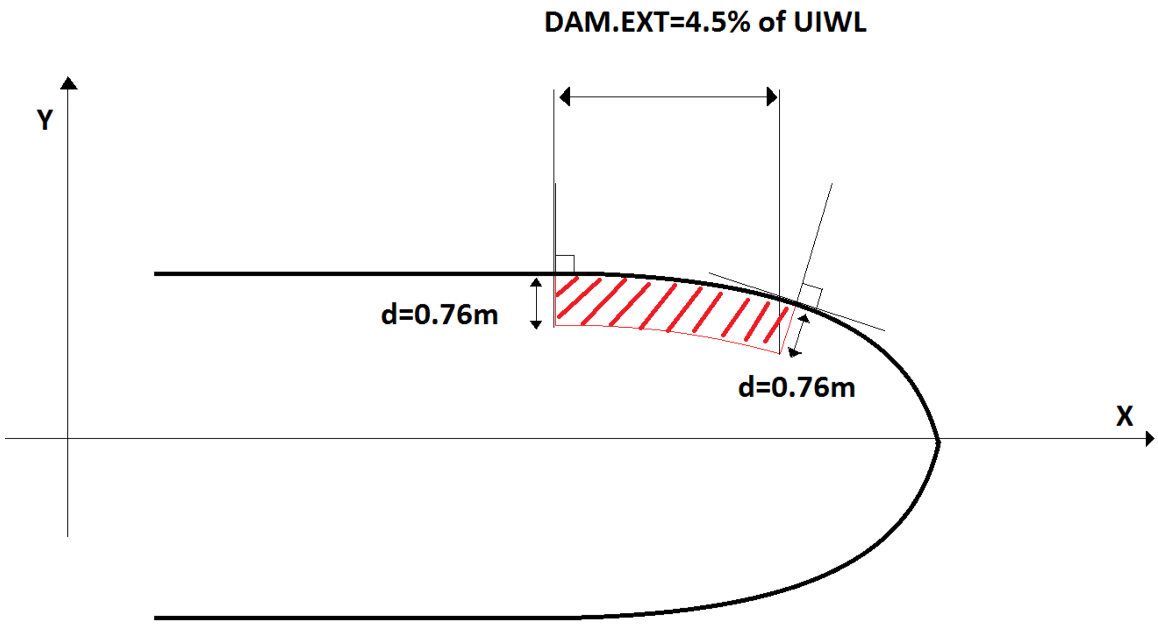

Figure 10. Damage length interpretation option ‘A’.

The damage length interpretation, named in this context as ‘A’, in

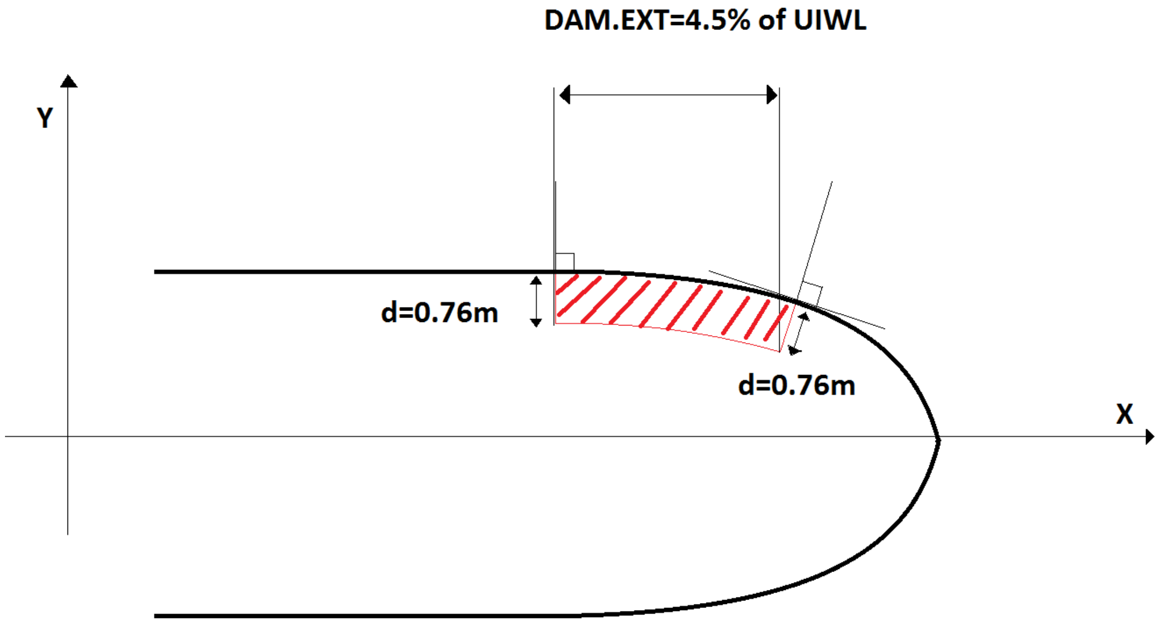

Figure 10 accounts the damage length as from the most extreme X-coordinated of the ‘damage-box’ at 0.76 m penetration. Because of hull curvature in the fore part of the ship, the most farthest x-coordinate of the ‘damage-box’ is found at the ‘damage-boxes’ corner that is 0.76 meters inside the hull. Same principle applies also to aft ship area where longitudinal length is 1.5% of UIWL.

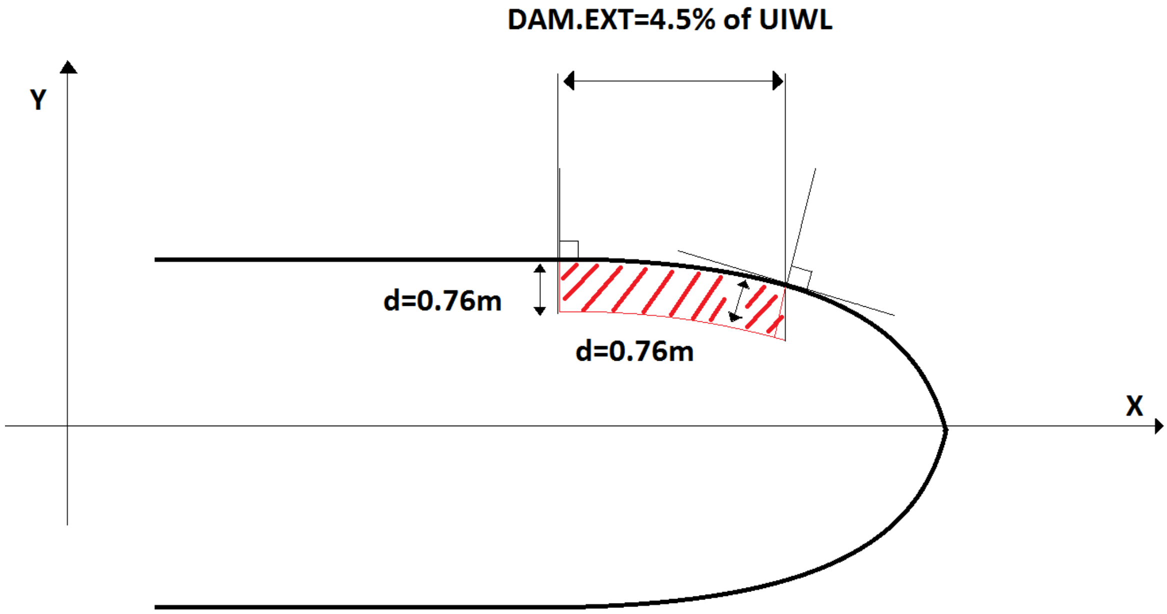

Figure 11. Damage length interpretation option 'B'.

The damage length interpretation, named in this context as 'B', in Figure 11 accounts the damage length as measured directly along the X-axis. In another words, the damage length is interpreted as a projected length and extended directly towards Y-axis, perpendicular to X-axis. This results that the 'damage-box' receives some amount of extra volume compared to option 'A', as the damage penetration is limited to the offset surface of the original ship hull, that is 0.76 meters inwards from ship hull directly towards centerline.

In both cases 'A' and 'B' the damage extent in x-axis direction is naturally same. What is different is the interpretation where the damage length is measured. The interpretation has effect to the shape of the 'damage-box', as in option 'B' the ends of the damage are parallel to y-axis and in option 'A' the ends of the damage are parallel to the normal of the hull. Because of these differences, the interpretation 'B' leads to slightly larger 'damage-box' by volume, even though the longitudinal extent remains same.

Currently there is not so much information about the interpretation of the Polar Code's damage stability. In master thesis by Ihalainen (2017), it is suggested that the interpretation should be similar as described in the alternative 'A', at least for vertical extent. At the time of writing the Polar Code has been effective such a short time. For this reason not many ships have been gone through class approval process yet or any public documents or guidelines has not been published yet. The fact that the interpretation for longitudinal extent is somewhat unclear, is that apparently any precedent case does not exist.

As one of the goals of this study is to create a tool for determining the relevant damage cases according to Polar Code's rules. **The interpretation 'B' is selected for this study** in order to keep the geometry of the 'damage-box' ambiguous and conservative from the safety aspect. This means also that damages vertical extent is measured directly in XY-plane level from the hull surface, and not from the inner parts of the 'damage-box'. The interpretation of vertical extent is illustrated in Figure 12 below.

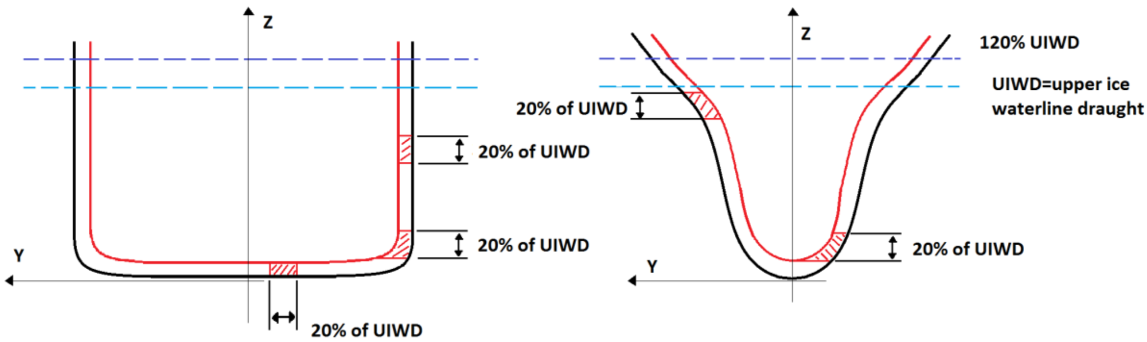

Figure 12. Ice damage's vertical extent with interpretation type 'B'.

For damages in the flat-bottom area, the vertical extent is interpreted to account damage the extent in Y-axis direction. One reason for this is that in practice, all ships have a double bottom that is at least 0.76 meters in height (IMO 2014). Also otherwise the damage penetration and vertical extent would be measured in same Z-axis direction. These interpretations are used in the ice-damage tool development. The interpretation of vertical damage extent at bottom area is also supported by Ihalainen (2017).

Damage stability analysis before the Polar Code was done for ships navigating in polar waters according to the probabilistic damage stability requirement as in SOLAS and other relevant requirements, such as OSV (offshore supply vessel) guidelines (IMO 2012) for offshore supply vessels. For passenger and cargo ships the probabilistic damage stability requirement was the only relevant requirement. By the nature of the probabilistic approach, some fatal damage cases are allowed to exist.

Polar Code makes damage stability requirements stricter as the existing rules must be followed but also the Polar Code requirement must be followed stating no damage cases are allowed that can lead to loss of stability. However, the damage extents are different in Polar Code, so direct comparison is not possible between these approaches meaning it is not relevant to say Polar Code sets always higher safety standards.

For passenger and cargo ships, the bottom area damages by Polar Code are also overlapping bottom damage scenarios defined in SOLAS. It (SOLAS) defines the damage cases to be studied in some situations with even larger extents, using the same requirement as the Polar Code that no damage case should not sink the ship. Maybe the most significant difference in SOLAS bottom damage is the vertical extent. For very large ships having breadth over 40 meters, the SOLAS bottom damage rule requires extent of 2 meters. However, for ships which breadth is less than 15.2 meters, Polar Code's damage extent is higher in the bottom area compared to SOLAS bottom damage rule, as SOLAS defines penetration value of B/20. SOLAS bottom damage scenarios are located in the hull area under the double bottom at any longitudinal and transversal position, meaning the locations of damages are similar to Polar Code rule.

The bottom damage extents by SOLAS are presented in below Table 2. SOLAS also states that if any smaller damage than specified by the maximum extents is more severe, such damage case needs to be considered. (IMO 2014) This comment about smaller and more severe damages is not included in the Polar Code.

Table 2. Maximum bottom damage extents by SOLAS (IMO 2014).

	For 0.3L from the forward perpendicular of the ship	**Any other part of the ship**
Longitudinal extent	$1/3L^{2/3}$ or 14.5 m, whichever is less	$1/3L^{2/3}$ or 14.5 m, whichever is less
Transverse extent	B/6 or 10 m, whichever is less	B/6 or 5 m, whichever is less
Vertical extent, measured from the keel line	B/20 or 2 m, whichever is less	B/20 or 2 m, whichever is less

Similar deterministic damage stability rule as in the Polar Code has been already introduced in offshore supply vessel guidelines (IMO 2012) where the transverse damage penetration is equal to Polar Code's value, but the damage length and height are different. The exact damage dimensions from OSV guidelines state (IMO 2012):

1. longitudinal extent:

1.1 for a vessel the keel of which is laid or which is at a similar stage of construction* before 22 November 2012: with length (L) not greater than 43 m: 10% of L; and with length (L) greater than 43 m: 3 m plus 3% of L;

1.2 for a vessel the keel of which is laid or which is at a similar stage of construction on or after 22 November 2012: with length (L) not greater than 43 m: 10% of L;

with length (L) greater than 43 m and less than 80 m: 3 m plus 3% of L; and with length (L) from 80 m to 100 m: $1/3L^{2/3}$;

2. transverse extent:

2.1 for a vessel the keel of which is laid or which is at a similar stage of construction before 22 November 2012: 760 mm measured inboard from the side of the vessel perpendicularly to the centerline at the level of the summer load waterline;

2.2 for a vessel the keel of which is laid or which is at a similar stage of construction on or after 22 November 2012: with length (L) less than 80 m: 760 mm; and with length (L) from 80 m to 100 m: B/20, but not less than 760 mm; The transverse extent should be measured inboard from the side of the vessel perpendicularly to the centreline at the level of the summer load waterline; and

3. vertical extent:

from the underside of the cargo deck, or the continuation thereof, for the full depth of the vessel.

, where L means ship length between perpendiculars and B is the breath of the ship at extreme width from outside of frame to outside of frame at or below the deepest subdivision load line.

The orientation of the damage penetration definition is different from the Polar Code, being orientated directly along the y-axis, as in the interpretation type 'B' described earlier. The damage length also differentiates from Polar Code in that sense that there is used only one length value. This can be understood in such way that the probability and severity of the damage is same at all longitudinal positions of the ship's hull. The damage's vertical extent is also assumed to be relatively much larger for OSVs, raging through the whole depth of the vessel. Even though the OSV guidelines state very similar damage case to be studied, according to the rulebook ice is not assumed to be the cause of the damage. The OSV guidelines (IMO 2012) is focused more on "near-costal voyages" and the rules are meant for ships ranging from 24 m to 100 m in length. These aspects are some possible factors that explain the differences in damage definition compared to Polar Code, as the distance to infrastructure and rescue is assumed to be close by. The OSV guidelines dates back to 1981 and are reviewed latest in 2012. (IMO 2012)

For new and existing tankers the damage stability regulations should not bring any changes, since double hull has been mandatory for tankers since 1983 (IMO 2015b), even though the damage stability requirement is not mandatory for existing ships. For constructional reasons the double hull is always at least 0.76 m, and usually even more. So the damage cases that needs to be studied are practically already included in the probabilistic damage stability study. (Aker Arctic, 2017)

The damage penetration value is fixed in Polar Code, compared to the other two extents. This means that same explanation about kinetic energy effecting the damage extents does not apply for the damage penetration. Even though no certain background was found the penetration value, according to Hovilainen and Vocke (2017), the value is conservative enough for penetration extent caused by collision with ice. As a number 0.76 meters relates translates 30 inch, or 2.5 feet, which gives some hint about the era and location when this value might be used originally in ship design. For example on year 1939 Finnish naval architect Mr. Jaakko Rahola (1939) was using already metric values in his early studies on ship stability, suggesting the 0.76 m value from British or North American person or organization. Another hint can be found from SOLAS 1960 treaty (IMCO 1960) which was still using imperial units as main units, but which were also translated metric units. The 1960 treaty states for example margin line to be 3 inches below the upper surface of bulkhead deck. In SOLAS 1976 treaty metric system is used solely for rule definitions.

The conclusion for the use of damage penetration value of 0.76 meters is, that same value has been institutionalized prior to year 1974 to possibly describe some structural extent related to potential location of flooding, which is not mentioned directly in the treaties. The value has apparently found to be sufficient as it has been used for example in SOLAS 2009 for minimum bottom damage penetration extent and minimum width for double hull in bulk carriers (IMO MSC.170(79)). In SOLAS 2009 treaty double bottom height is for the first time defined with mandatory minimum value, being 760 mm for vessels other than tanker (IMO 2009).

3 Intact stability calculation study

3.1 *Sample ships*

One goal of the study is to develop a method for calculating the effect of icing on intact ship stability. This means a tool that can determine the amount of ice accretion based on the 3D ship model and then implement the effect to ship stability calculations. In order to make reliable stability calculations with the developed tool, the ship models used in the tool development should be as realistic as possible and fulfill the structural requirements as required for any SOLAS 2009 ship, especially for the damage stability calculations. The most essential parts of the ship model used for intact stability tool development are the superstructure and the hull form, which have direct effect on ship stability and the ice accretion. Three ship models are selected for the example calculations and one test-case ship is created for the tool verification purposes.

One of the sample ships represent realistic passenger ship passenger vessel and other two are relatively realistic bulk carrier and naval frigate. All sample ships are utilized already in the tool development phase to ensure the final outcome to be as compatible with several ships as possible.

The verification of the tool's functionality is tested on a very simple shaped ship model, created solely for that purpose of the tool verification. The test-case ship has only rectangle-shaped decks to allow easily verify the functionality of the tool, meaning that the areas and center of gravity locations are simple to calculate manually and see possible differences compared to results obtained from the developed tool.

The test-case ship called POLARTEST is illustrated below in Figure 13. The functionality of the icing tool is verified with this test-case ship to ensure the tool works as intended.

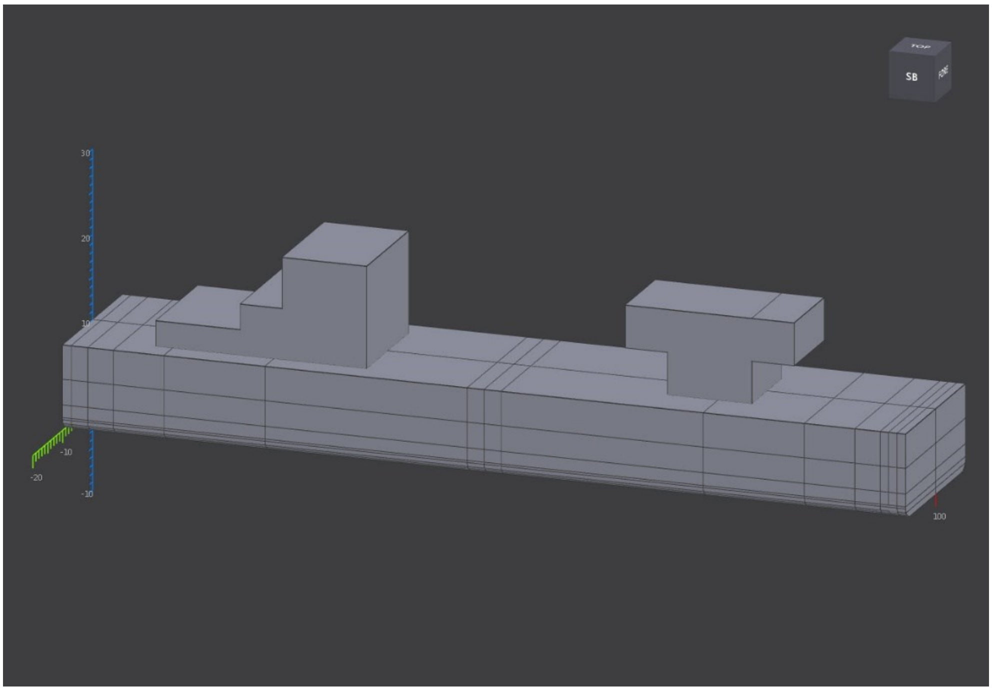

Figure 13. Test-case ship model, POLARTEST, used in the tool verification.

A 240 m long cruise ship, FLOODSTAND-B ship, is selected to be the primary ship model used in the case studies. The FLOODSTAND-B ship is designed by Meyer Werft GmbH shipyard and it is fulfilling relevant SOLAS 2009 requirements for the ship type in question, as its building was imaginarily planned to start in July 2010 (Luhmann 2009). It has been used also earlier as a test case ship in other studies where the 3D NAPA model was finalized. However, as the FLOODSTAND-B design has not gone through classification society's approval, it cannot be considered completely realistic ship design, but is still sufficient and good for the purposes in this study, as it has been good case study ship in the original FLOODSTAND project (Jalonen et al 2012) (Luhmann 2009).

This particular ship, model and often passenger ships in general, do not have double sides. The ship has decks high up from sea level where icing has larger effect for the stability. Cruise ship model offers thus interesting platform for both intact and damage stability study. This size cruise ship is also in the same magnitude of cruise vessels that are likely to be used in polar areas for tourist cruises. Larger cruise ships are not yet seen as possible candidate for polar waters because of deeper draught and because of the industry of Arctic and Antarctic expedition cruises is still being relatively young and the customer base is not as wide as in traditional cruises (Ihalainen 2017). The studied cruise ship demonstrates how conventional cruise ship design behaves under the altered loading condition due to icing, taken into account as described in the Polar Code. The main particulars of the cruise ship are shown in Table 3 below. The table includes information about the location of freeboard, which is the highest limits of buoyant hull. It is important limit for interpreting the later results, as it has direct effect on the immersion angle of freeboard. Openings are not used in the example calculations since all studied ship models do not include those and would thus make the comparison of results more complex. Profile view of the FLOODSTAND-B is presented below in the Figure 14 and general overview of its 3D model in Figure 15.

Table 3. Main dimensions of studied passenger ship FLOODSTAND-B. (Luhmann 2009)

LOA	238,00 m
Length pp	216,80 m
Beam moulded	32,20 m
Freeboard/bulkhead deck location	9,80 m
Draught design (approx.)	7,20 m
Draught max (approx.)	7,40 m
Tonnage (approx.)	63000 GT
Number of passengers + crew	1800 + 600

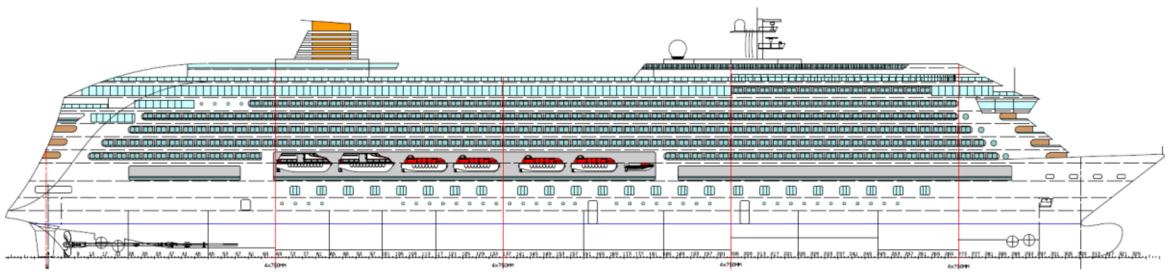

Figure 14. FLOODSTAND-B profile view (Luhmann 2009)

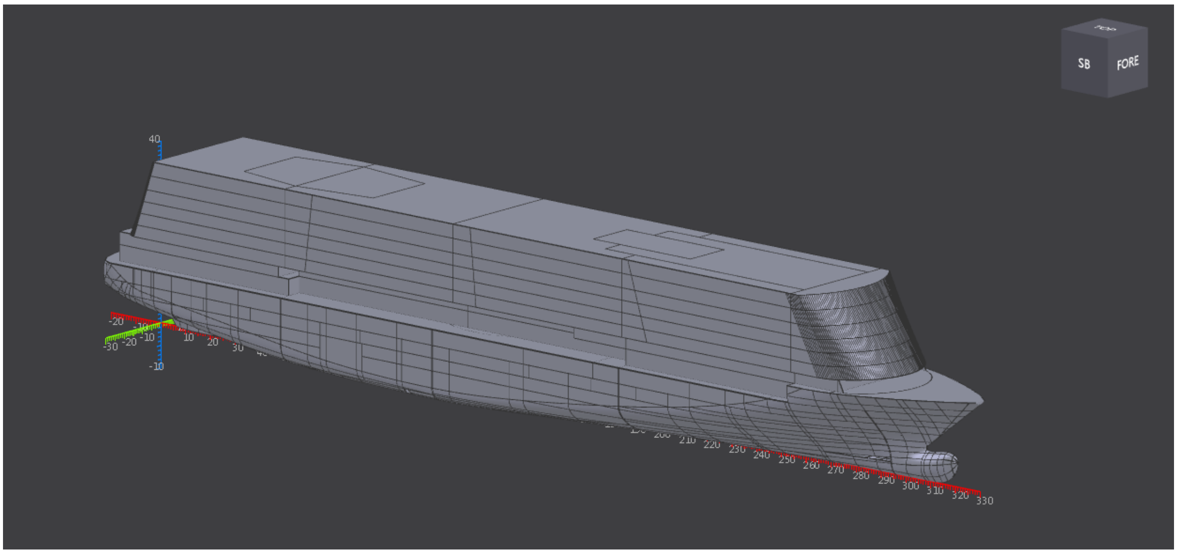

Figure 15. Passenger ship FLOODSTAND-B 3D-model (Luhmann 2009).

The other two sample ships used for intact stability case studies are so-called "demo projects" included in the NAPA software. The bulker and naval frigate are not designed as intended to be an actual ship to be built, but they still represent the appropriate ship types well enough for the proposes of this study. Both of the vessels have typical hull form of the ship type with adequate superstructure and loading conditions. The loading conditions are the main source for possible inaccuracy, as the ships models have not gone through classification process and thus the structures and compartments may be unrealistic on some level. However both ship designs provide good reference for the icing study as the superstructures are adequate and give good reference how much ice will accumulate. Main dimensions and other relevant information of the ships are presented in Table 4 below. General arrangements of the bulker and frigate are shown in Figure 16 and Figure 17, and the 3D models of the ships used in calculation are presented in Figure 18 and Figure 19.

Table 4. Main dimension of used bulk carrier and naval frigate.

	Bulker	**Frigate**
LOA [m]	224.0	148.2
B [m]	36.0	15.9
T [m]	15.0	4.9
Freeboard/bulkhead deck location [m]	Z=21	Z=9.4
Displacement [tons]	101600	5400

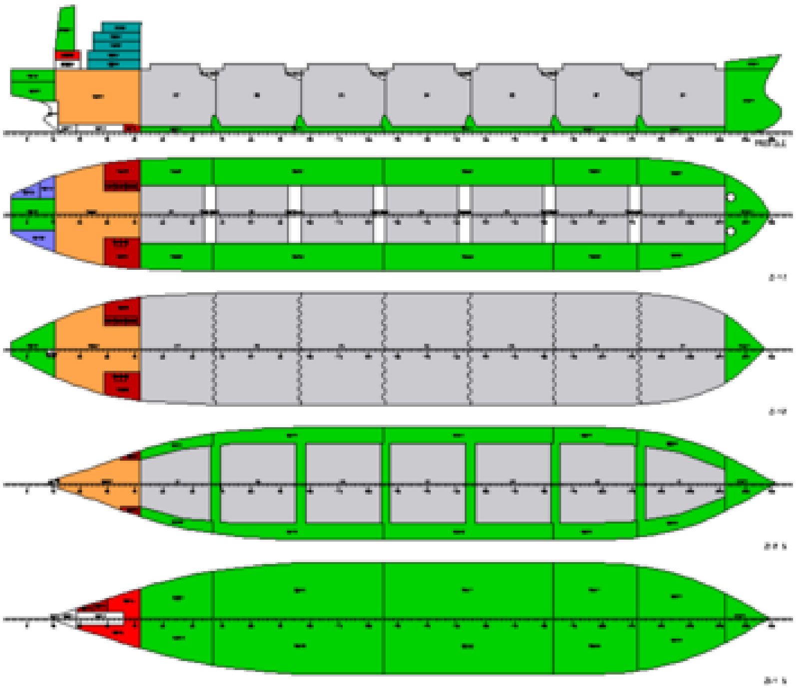

Figure 16. General arrangement of studied bulk carrier (NAPA 2017).

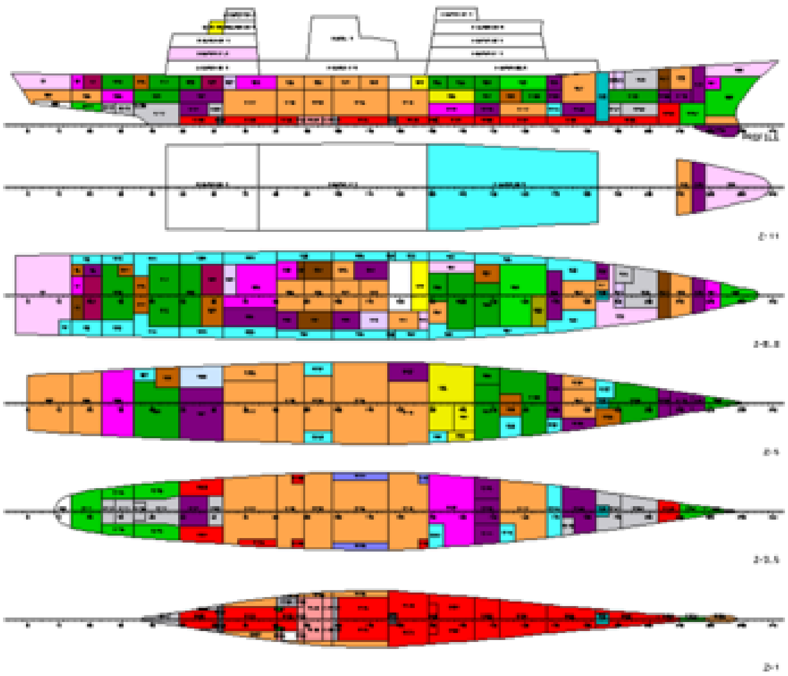

Figure 17. General arrangement of studied naval frigate (NAPA 2017).

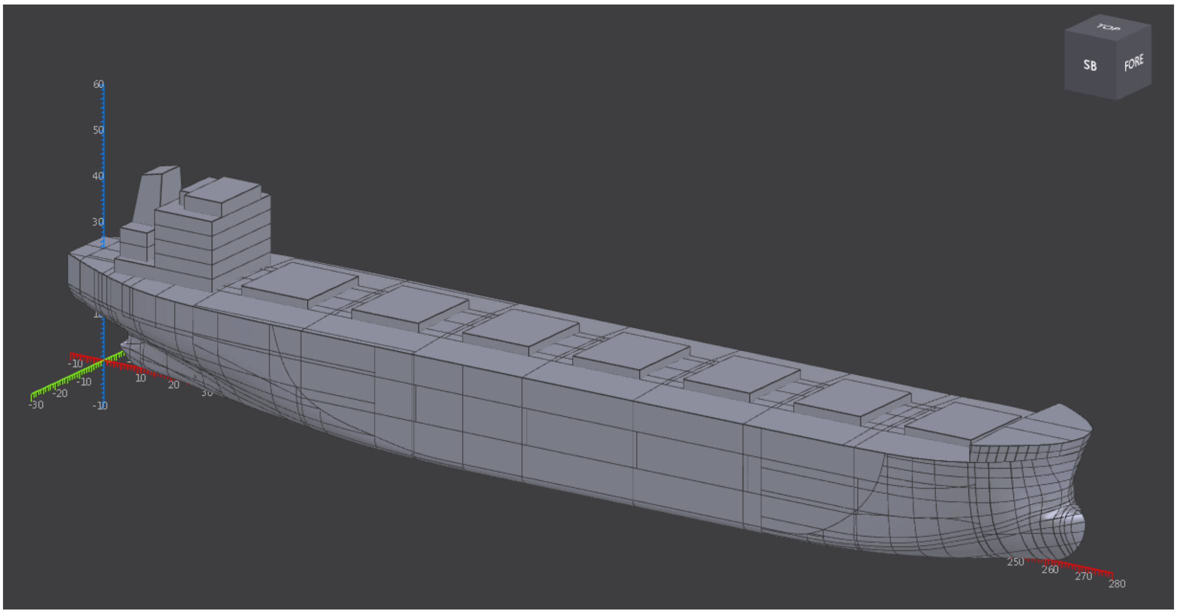

Figure 18. Bulk carrier, NAPA D-Bulker 3D-model.

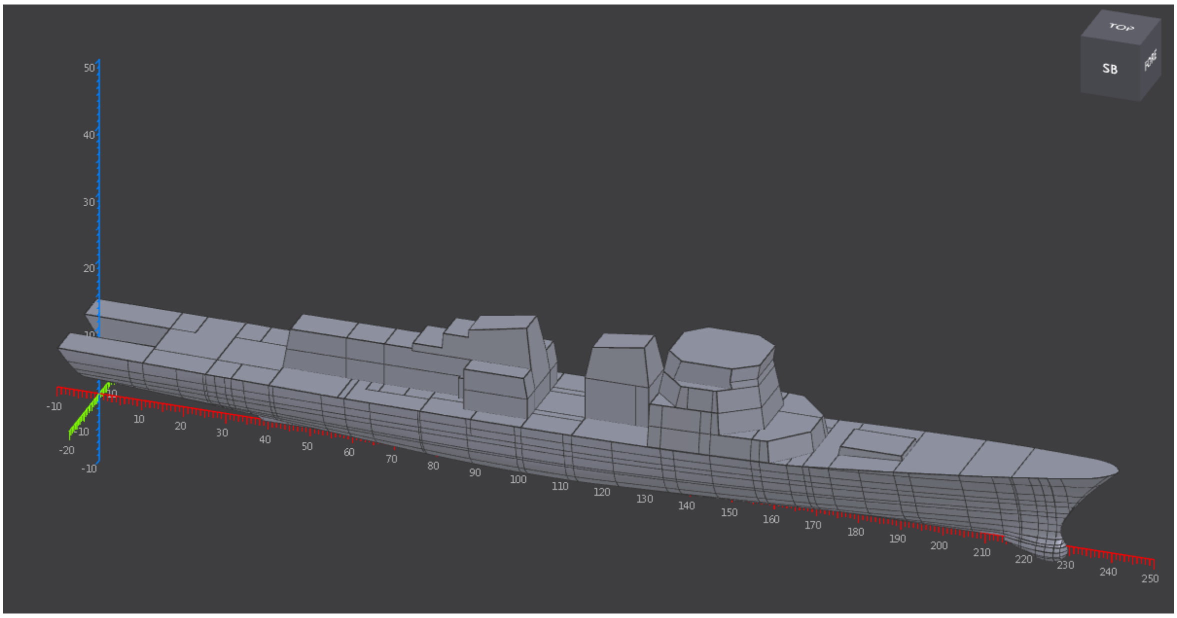

Figure 19. Naval frigate, NAPA D-Frigate 3D-model.

3.2 *Intact stability tool development*

Currently there is no ready-built tool for taking into account the icing related change of loading condition, which affects the ship stability. Implementing and developing a new intact stability tool for the NAPA software is based on the use of a 3D ship model and loading conditions of the ship. The resulted ice mass, which is calculated based on the 3D model, is added to relevant loading conditions for the intact stability calculations.

In some cases the calculation of added mass from icing can be very time-consuming if carried out completely manually. Also the risk of human errors will exist. These problems arise especially if the ship superstructure is complex-shaped which leads to high number of surfaces that needs to be taken account separately.

The determination of added mass due to ice has two main steps. First, calculation of the area and centroid (noted as CoG as the ice mass is added to these points) of each deck and the lateral projection. Second main step is that the ice load is added on these areas and the combined center of gravity of the decks and lateral projection is calculated to represent the added mass at single coordinate. Below equation is used for calculating the centroid (noted as CoG) of decks, using the sections above and below the deck (same equation applies for all X, Y and Z coordinates of CoG):

$$CoG_d = ((CoG_{DA1} * A_{D1}) - (CoG_{DA2} * A_{D2}))/abs(A_{D1} - A_{D2})$$

where; CoG_d is the center of gravity of exposed deck, CoG_{DA1} is center of gravity coordinate for lower section below deck, A_{D1} is area for lower section below deck, CoG_{DA2} is center of gravity coordinate for upper section above deck and A_{D2} is area for upper section above deck. The tool fetches the values CoG_{DA1} and CoG_{DA2} automatically from the geometry of the sections above and below the deck.

In case the denominator in above equation gets value 0 from the reduction of areas, the result is considered directly by finding the average of the coordinates of the upper and lower sections. Equation for decks' and lateral projection's combined ice mass coordinates, same equation applies for X, Y and Z coordinates is presented below:

$$CoG_{ice\_n} = (LCoG_n * m_l + DCoG_n * m_d)/(m_l + m_d)$$

where; CoG_{ice_n} is the coordinate value of lateral projection's and decks combined center of gravity, $LCoG_n$ is coordinate n for lateral projection, m_l is ice mass on the lateral projection, $DCoG_n$ is coordinate n for deck area and m_d is the ice mass on deck.

The projected lateral area of the superstructure is obtained by creating a union curve from Y-sections taken across ship breath, to describe the lateral projection. The curve can be made with a built-in feature in the software used. Using directly a calculation section at coordinate Y=0 of the ship is not a good approach for making the profile curve since the superstructure can be unsymmetrical in some ships. This would cause the profile curve to describe only the center line and not the actual side projection.

The aim of the developed tool is to automatically determine the vertical and lateral areas of the superstructure from the 3D model using very little manual input from the user. The required inputs are the Z-coordinates of each exposed deck, or other horizontal flat area, in the superstructure. In addition the offset value for sections below and above the decks can be given. For the stability calculation the user needs to define in which loading conditions he or she wishes to add the mass, these loading conditions can be for example heaviest and lightest loading condition. User inputs needed for intact stability tool is described in Table 5. User inputs for the developed intact stability tool. below.

Table 5. User inputs for the developed intact stability tool.

Input	Explanation of input
Z-coordiantes of exposed decks	Used to indentify the decks in exposed superstucture
Offset value	Used for generating sections below and above decks
Trim (opt.)	Optional, if no loading condition exists
Draught (opt.)	Optional, if no loading condition exists
Loading condition(s)	Direct way to determine floating position for stability calculation

The process of the intact stability tool is explained below with short step-by-step description.

1. User inputs: locations of superstructure decks, loading conditions to study, (opt.) offset for deck comparison (by default 0.1 m), (opt.) trim, (opt.) draught
2. With deck locations, sections above and below each decks is created using the offset value
3. The offset deck sections are reduced from each other, resulting the exposed deck area. The area representing exposed deck area is located Z-coordinate as original user input for that deck

4. Centroid (CoG) of exposed decks is calculated with built-in functionality
5. Ice mass 30 $\mathrm{kg/m^2}$ is multiplied with decks' areas
6. Exposed decks mass and CoG is combined
7. Lateral projection curve of the ship above waterline is created
8. The additional 5% area is calculated for lateral projection
9. Ice mass 7.5 $\mathrm{kg/m^2}$ is added to the projected area
10. Ice mass of 7.5 $\mathrm{kg/m^2}$ with additional 10% increase is added to the 5% addition of lateral area
11. Combined mass and CoG of decks and lateral projection with the extra allowance, is combined to a single point
12. The resulting mass and its CoG is added to relevant loading conditions
13. Intact stability criteria are calculated for these loading conditions with relevant criteria

The verification of the tool is one part of the intact stability tool development. The verification is carried out with the test-case ship POLARTEST, which has simple shaped decks and superstructure for allowing simple manual calculation of areas.

Based on the geometry of the test-case ship POLARTEST, areas of lateral projection and decks are calculated manually. As a result, total ice mass of 74552.25 kg or about 74.55 tons is obtained. The combined center of gravity for the ice masses on decks and lateral areas is calculated to be at X=50.89, Y=0, Z=12.02.

The developed tool would then add this mass to the relevant loading conditions as a mass load at the obtained coordinate for stability calculations. After that intact stability could be calculated with relevant criteria, taking into account the effects ice accretion. Any intact stability criteria is not applied for this test-case ship, since it does not represent realistic ship design and thus would not give reliable insight for the stability aspect.

These ice mass and CoG results verify the correct functionality of the intact stability tool on a ship model having simple superstructure and hull, as the obtained results are identical to values calculated manually. Figure 20 shows more detailed icing results for the POLARTEST ship model obtained with the developed tool and Figure 21 shows the superstructure deck plans and profile of the ship.

Intact stability results

NAPA/D/LD/170619 DATE 2017-06-27
POLARTEST/A TIME 13.23
POLARTEST USER NTHU
1

##

Areas and CoG -locations of superstructure decks from lowest to highest.

Area at z-coordinate level 10 m is: 1550 m2 and CoG is (54.5968, 0, 10) Area at z-coordinate level 13 m is: 140 m2 and CoG is (15, 0, 13) Area at z-coordinate level 16 m is: 70 m2 and CoG is (22.5, 0, 16) Area at z-coordinate level 20 m is: 200 m2 and CoG is (75, 0, 20) Area at z-coordinate level 22 m is: 140 m2 and CoG is (30, 0, 22)

Deck's CoGs (xyz) are 51.1905 0 12.1524 [m] and ice mass on decks is 63000 kg.

Area of the lateral projection above waterline is 1460 m2 for load1 and m2 for load2, this number includes the areas for both sides of the ship.

For lighter LC (load1), lateral projections CoG (xyz) is 49.2808 0 11.274 [m] and the ice mass for lateral areas is 11552.2 kg including both sides of the ship. The lateral ice mass consists of 10950 kg from lateral projection, and 602.25 kg that takes account discontinuous surfaces (as per Polar Code).

For heavier LC (load2), lateral projections CoG (xyz) is [m] and the ice mass for lateral areas is 602.25 kg including both sides of the ship. The lateral ice mass consists of kg from lateral projection, and kg that takes account discontinuous surfaces (as per Polar Code).

FINAL RESULT, ADDED TO SELECTED LOADING CONDITIONS (load1 and load2): Combined center of gravity for ice masses is: FOR LIGHT LC load1 : (X=50.8946 , Y=0 , Z=12.0163) and the total ice mass is 74.5522 ton. FOR HEAVY LC load2 : (X= , Y= , Z=) and the total ice mass is 63.6022 ton.

##

Figure 20. Intact stability results on test-case ship POLARTEST.

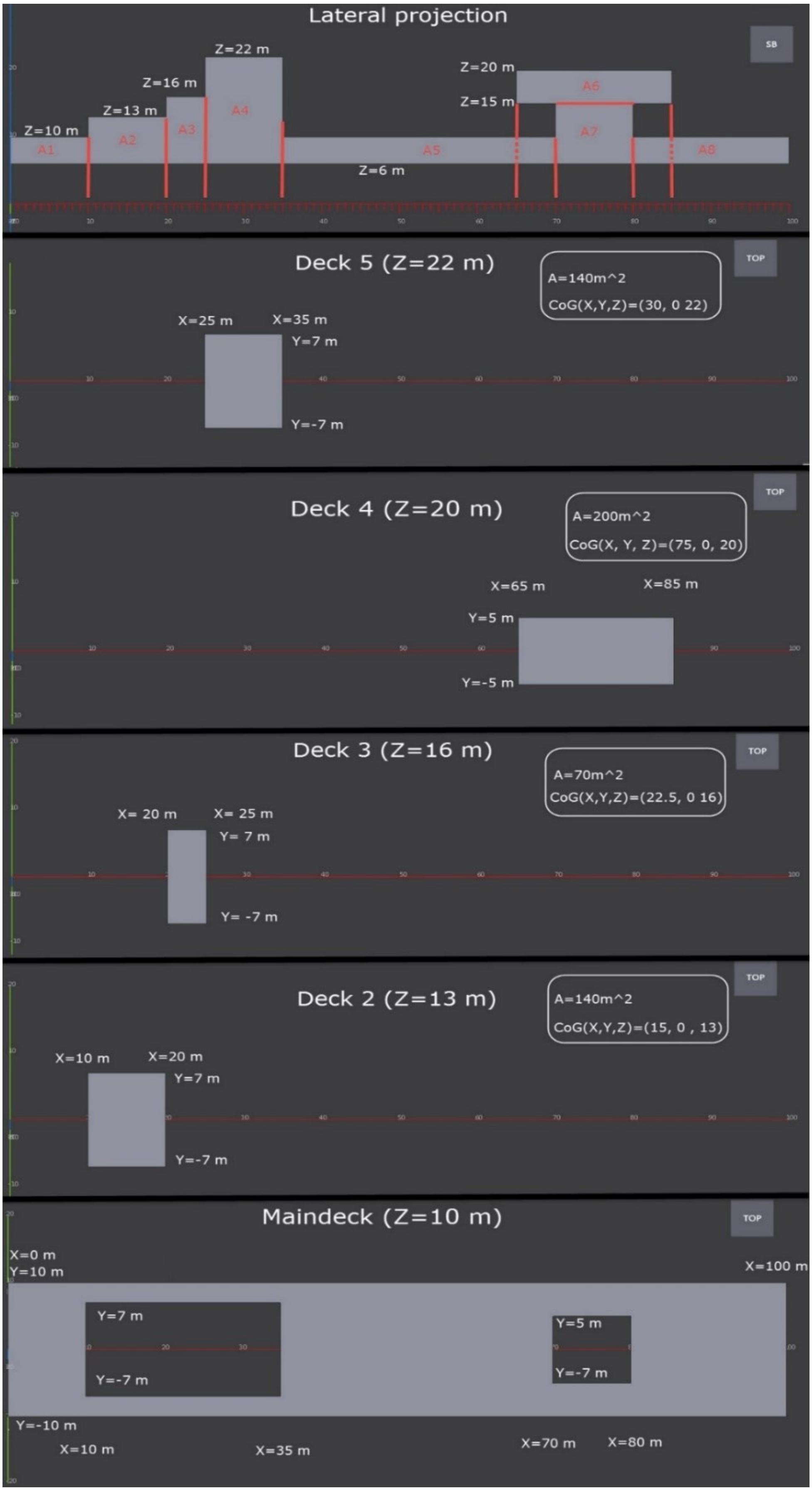

Figure 21. Deck plans and lateral projection of the test-case ship.

4 Damage stability calculations

Sample ships

Selected ship model should represent as realistic case as possible, where the ship is already designed to fulfill the existing damage stability regulations such as in SOLAS and MARPOL. In case of damage stability study, it is even more important that the used ship
4.1 model is as close to an actual ship design and has properly defined compartments and watertight subdivision.

The ship used in damage stability study is the same ship as mentioned in the previous chapter concerning intact stability. FLOODSTAND-B is good reference and interesting for the study since it is designed to fulfill the existing regulations for this type of conventional passenger vessel, in accordance to SOLAS 2009 (with required index R=0.78222 and attained index A=0.8005) (Luhmann 2009).

It also does not have double sides as it is a ship not intended for carrying substances that might leak out to the sea in case of an environmental accident. However some precaution is needed when analyzing the results, since the FLOODSTAND-B ship model is project ship and not gone through classification society's inspection as ships that are meant to be built. It is still excellent ship model for damage case study, even though there is not complete certainty of A-class structures and compartment connections even though those details exist in the used ship model. The watertight subdivision of the FLOODSTAND-B is illustrated in Figure 22. The watertight subdivision used in damage stability calculations, are presented also in higher detail in Appendix 1.

Studying the damage stability with tankers or cargo vessels is not seen that interesting as they are usually designed to have double sides to fulfill the stability requirements and to prevent pollution in case of grounding or collision. The double side design is very often used for all types of ships intended for polar waters. According to the interview with naval architects Hovilainen and Vocke (2017), most of ice-going ships that Aker Arctic have designed, are built to have at least 760 mm double side. Reasons for this is to get easily the required safety level for damage stability and pollution prevention, but also to insulate the ship interior from outside weather.

FLOODSTAND-B is also good sample ship for the calculation since it double bottom height larger than B/20, for which reason the Regulation 9 in SOLAS 2009, concerning bottom damages, is not studied in the original FLOODSTAND-B stability study (Luhmann 2009). The Polar Code requires always to study also bottom damage scenarios, as the whole submerged hull up to 20% above upper ice waterline (or 20% of damages longitudinal extent) is considered to experience damages (IMO 2015a).

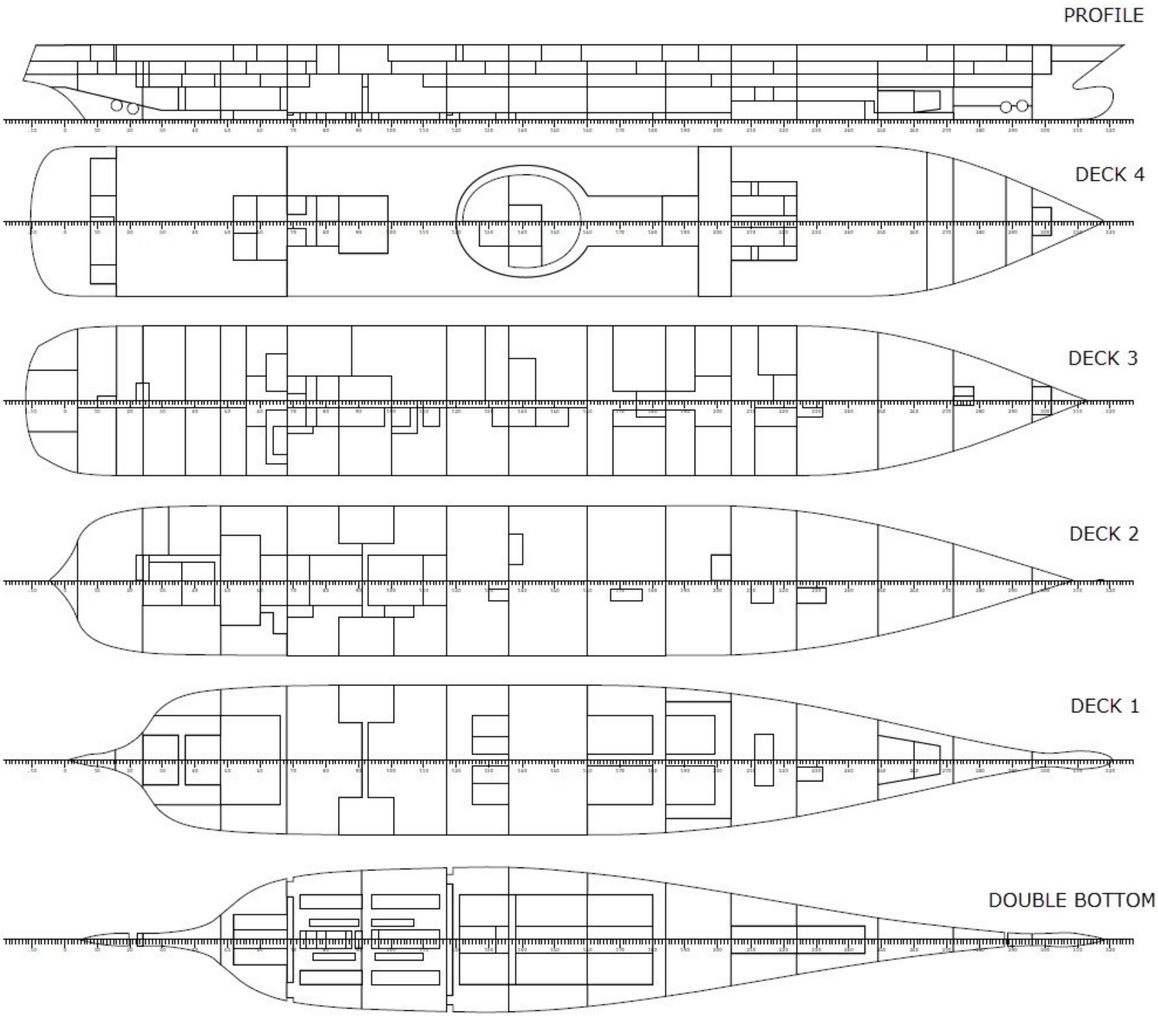

Figure 22. Water tight subdivision of FLOODSTAND-B (Luhmann 2009).

4.2 Damage stability tool development

Polar Code adds a new damage stability requirement, which follows a deterministic approach. This means that the ship is exposed to a pre-determined damage scenario that can take place anywhere in the submerged hull and 20% above the deepest designed waterline. The extent of the pre-determined damage scenario is described in the Polar Code (2015a) as stated also earlier and below:

1. the longitudinal extent is 4.5% of the upper ice waterline length if centred forward of the maximum breadth on the upper ice waterline, and 1.5% of upper ice waterline length otherwise, and shall be assumed at any longitudinal position along the ship's length;

2. the transverse penetration extent is 760 mm, measured normal to the shell over the full extent of the damage; and

3. the vertical extent is the lesser of 20% of the upper ice waterline draught or the longitudinal extent, and shall be assumed at any vertical position between the keel and 120% of the upper ice waterline draught.

To create a new tool for calculating this deterministic damage stability, it is needed to identify the relevant aspects that need to be taken into account. The key requirements are; (1) make sure all conventional hull forms work with the tool, (2) penetration in the normal direction of the hull is taken account correctly and (3) other damage extents by ship particulars are taken account correctly.

Polar Code does not explain how the damage extent should be considered in bow, aft and bottom areas of the ship, as discussed in chapter 2.4.2. In these areas, the concepts of damage length and height are unambiguous. For example, is the damage height in the bottom of the ship measured in Y- or Z-direction? Alternatively, is the damage length measured in the aft ship area plainly in X-axis direction or by taking account the hull curvature so that the length is measured along the hull surface?

In this study, these damage extents are interpreted as introduced earlier in the chapter 2.4.2. For this reason that damage height is measured on different direction at bottom area, the developed tool has separate part for bottom damage filtering.

The tool is developed to be easy to use and efficient in damage generation and filtering the relevant damages. Inputs that the user needs to give are similar what is needed in existing probabilistic damage generation and calculation methods. Most important input is the subdivision table that describes the watertight limits of the ship. The ship model itself needs to be prepared to such level that it has the final hull form and room arrangement. In addition, possible openings and other objects related to unrestricted flooding need be inputted for the damage generation. Openings and compartment connections are one important detail to be modeled and described in table format, since those have great effect to where the water can flow from damaged compartment. With these information and the measures of the damage, the damage filtering tool finds all possible damage scenarios that can occur in the limits given by the Polar Code.

There are two main reasons why current approaches do not work with the deterministic damage cases as described in the Polar Code. First issue comes with setting damage penetration in normal direction to the hull surface. This problem was solved by interpreting the Polar Code rules so that damage extent is limited to an offset surface that is 0.76 meters inwards from the original hull in normal direction, as illustrated in Figure 12. The interpretation was chosen since it is conservative solution from the two options discussed in chapter 2.4.2. In addition, this interpretation was seen to be simpler and more robust to implement for the tool to be created. Without the limiting surface, also rooms and watertight compartments located closer to center line of the ship would be included, leading to very large number of irrelevant damage cases and resulting in longer computation time and the risk of irrelevant damage cases being included in the results.

Main challenge of the developed tool is the selection of the relevant damage cases. The issue of damage case filtering results can be approached from three directions: (1) required that the tool finds all relevant cases and not any wrong cases, (2) tool finds most of the relevant cases and not any wrong cases and (3) tool finds most of relevant cases and some irrelevant are left in the results.

The logic behind damage case generation in NAPA is to create all possible combinations of damages inside the longitudinal extent limits and watertight subdivision limits. The longitudinal extent in damage generation means how many adjacent compartments can be damaged. This is one of the inputs set by the user, ranging usually from one to three zones. Three adjacent-zone damage is seen possible since for example with 300 meter-long ship the longitudinal damage extent would be 13.5 meters, which could realistically extend over one small watertight zone, leading to 3-zone damage. Based on this the damage cases are created using the watertight subdivision limits of the ship, first creating all single compartment damage cases, after that two compartment cases and so on, until all needed cases are generated. Usually this means that hundreds of damage cases are created, including too long, too short, too high and too low damage cases. These irrelevant cases need to be filtered out. In other words, only those damage cases that can be created by placing the ‘damage-box’ which dimension Polar Code defines, into certain location are relevant. The filtering of damage cases in the developed tool is based on a geometric study of the rooms included in the damage cases.

In theory, the geometrical study of rooms involved in the damage case may seem to be simple. However, the geometry of rooms in the ship may be very complex and for that reason that there is almost infinite number of different room and watertight compartment geometries and combinations of compartments. For these reasons it is practically impossible to develop damage case filtering that is always 100% functional, finding all relevant damage cases and removing all irrelevant ones. For ships that have box-shaped watertight compartments and rooms, the damage case filtering that is developed in this study, should work most efficient way.

The efficiency and robustness of the tool is tested with a very simple ship model that is designed for this testing purpose to prove that the geometry filters in the tool work as intended. The test ship model has box-shaped compartments and conventional hull form with vertically flat aft and bow. Below in Figure 23 and Figure 24 are illustrations of two possible damage case scenarios, illustrating how damage location has effect on which compartments will be flooded.

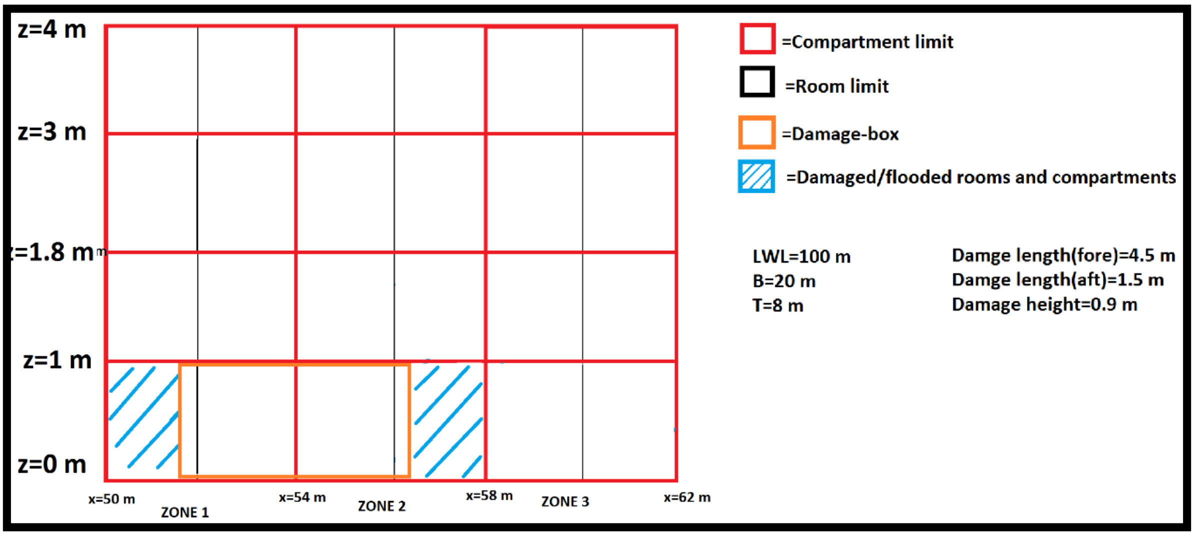

Figure 23. Damage in fore-area. Two zones on one deck flooded.

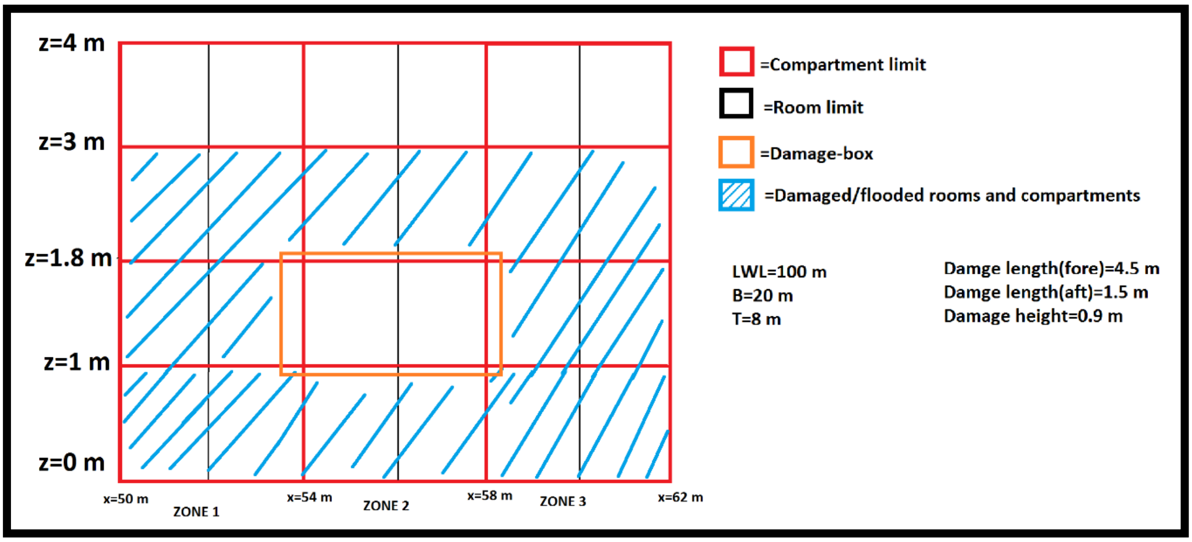

Figure 24. Damage in fore-area. Three zones on three decks are flooded. Largest possible damage.

Figure 23 and Figure 24 illustrates how the location of deterministic 'damage-box' can affect how many compartments are flooded. The red lines marks the limits of watertight compartments and which all have two non-watertight rooms inside of them. The dimensions of the ship and its compartments are chosen just to highlight the possibilities how the damage can flood various compartments in some scenarios. In real ship design, the situation where three adjacent compartments are flooded should be quite rare, but possible. More unlikely is the situation where the vertical extent of the damage reaches over one deck, since the vertical extent is rather small compared to typical deck spacing. In case of larger ships, the possibility becomes higher for both scenarios. For example for a 300 m-long vessel the damage's longitudinal extent at fore area would be 13.50 m, which can realistically be the length of a compartment. A ship with draught of 15 m would lead to vertical extent of 3 m, if the length of the ship is more than 333.3 meters (for example, one of the largest passenger vessels, M/S Oasis of the Seas, has draught of 9.1 meters and length of 360 meters). This would result the deterministic damage in the fore area to be 16.2 m in length and 1.82 m in vertical extent.

The damage filtering is based on three main levels: (1) filtering for that damage penetration is not too large, (2) filtering based on damage length and (3) filtering based on damage height. The first filter checking that damage is not too much inside the ship is just a precaution since all 'damage-boxes' are already limited to the offset surface of the hull, that is 0.76 meters inwards from hull, at the damage generation phase, which is done automatically in NAPA for Design software.

The filtering based on damage length includes two main checks. In three-zone damages the middle zone cannot be too long so that 'damage-box' reaches to all zones. The second main check is that single-zones damages cannot be too short. If the zone length is less than the damage length, the resulted damage will always be larger and because smaller damage cases are not included as per Polar Code, these cases are irrelevant. Third possible damage case in respect to length is two-zone damage. These should be usually be always possible cases, however the inspection for too short cases is included in the tool in a similar way as for one-zone damages. The damage length information for each case is obtained from table that NAPA damage generation produces automatically with the help of subdivision table created by the user.

The filtering for damage height is based on room geometry. The filtering tool inspects which rooms are included in the damage case and reduces the volume of the rooms that is more than 0.76 meters inside the hull. The resulted rooms describe the potential area and space where the 'damage-box' can be placed. Using these rooms the tool checks the second most highest and second lowest limits of the rooms. If distance between these points is less than damages vertical extent, damage is included.

The developed tool for damage generation and damage case filtering works as described below:

1. User inputs: subdivision, compartments and compartment limit table, hull for damage calculation, table for results and designed highest ice waterline.
2. 0.76m smaller offset hull surface is created and smaller damage hull from it.
3. Coordinate system of the project is checked and taken into account
4. All damages based on the subdivision are generated with NAPA built-in feature, penetration is limited to the created offset hull

5. A check is made to filter out damage cases in which compartments are inside the offset hull and thus relevant, cases having compartments too much inside are removed
6. Damage cases having compartments completely below double bottom are removed, damage cases at double bottom area are considered later
7. Damages are filtered by length in fore and aft part of the ship using damage extent information from automatically created table based on the subdivision table
8. Damages are filtered by height using the information of rooms upper and lower limits that are included in the damage case. The used rooms are reduced so that they describe only the area/volume at 0.76 m extent from hull
9. Empty and duplicate damage cases are removed

The functionality of the developed tool is verified with the test-case ship model POLARTEST. The subdivision of the POLARTEST is simple with vertical and horizontal bulkheads, making the watertight compartments to be box-shaped apart from the side that is limited to the hull. The compartment limits are selected such way that irrelevant cases and relevant cases are easy to notice when analyzing the results. Verification of filters is carried out manually, inspecting all resulted damage cases that are remained after using the tool. Results are gathered in Table 6 below showing the how the amount of relevant cases decreases after each filter. The damage extents for POLARTEST are 4.5 meters in length at fore area and 1.5 meters at aft, and 0.9 meters in height at fore area and 0.3 meters at aft.

Table 6. POLARTEST, damage case filtering test results.

	Port, side	**Port, bottom**	**Starboard, side**	**Starboard, bottom**
All possibilities	642	65	642	65
After offset/limit filter	447	65	447	65
After length filter	244	25	244	25
After height filter	149	20	149	25
After empty-case filter	149	20	149	25
After duplicate filter	142	20	142	25

Manual verification of resulted damage cases proves that the developed tool works as intended with the simple test-case ship, finding all relevant damage cases. Testing of the damage generation and filtering tool with test-case ship POLARTEST proved the tool is capable to filter out all irrelevant cases and find all relevant damage cases. The test-case ship has 150 rooms in the area where the damages can occur. The room limits are same as the subdivision limits. The compartments and subdivision are symmetrical over the centerline. All possible damage cases, limiting to offset surface and reaching from one to three zones located over the whole draught of the ship, accounts to 1414 damage cases including both sides of the ship, including the bottom areas. After filtering the potentially relevant cases based on the length and vertical height requirements, total of 329 relevant damage cases are found.

The tool account the bottom damages exactly the same way as side damages, apart from the differences that damages vertical extent is measured in Y-axis direction (at the bottom area noted as transversal extent) and that damage height filtering is slightly different. The difference in transversal extent filtering comes from the centerline, as some of the compartments may extent over it. In these cases the damage's transversal extent is limited to start or begin at center line. Figure 25 illustrates the situation.

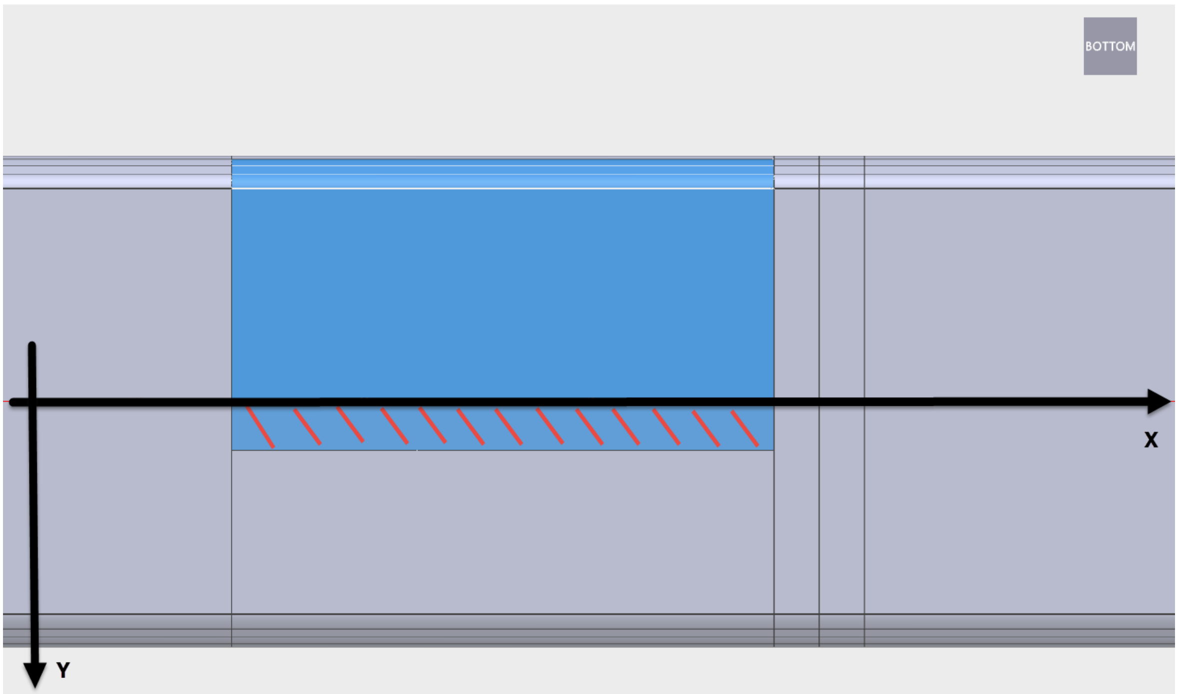

Figure 25. Compartment (marked with blue highlight) extending over centerline at bottom area.

The used subdivision of the test-case ship model can be found in the Appendix 6. The number of relevant damages in case of 100 meter-long ship may be larger than for real ships, since the spacing of the bulkheads is very short at some hull areas for the testing purposes. These areas of tighter bulkhead spacing are aft, amidships and fore. Amidships area is especially interesting as there the damage length value changes as the rule defines. These three areas cover different scenarios by the damage length to be used and the placement of the bulkheads is carried out so that all possible combinations of damages are occurring. With different bulkhead and deck spacing the functionality of the tool can be validated for the simple box shaped compartments.

5 Results

5.1 Intact stability

Example calculations of intact stability due to icing are done to further validate the functionality of developed tool and showcase how the icing affects different ship models that are designed before the Polar Code came into force and not thus not designed especially for these requirements. The loading conditions used in the calculations are aimed to represent the extreme loading situations that are still expected to be used at sea, representing a fully loaded ship and a ship in lighter loading condition when arriving to port with little or no cargo. The intact stability calculations are carried out with port side heel (positive angles).

Ice accumulation and its effects on ship stability are depending only on the shape of the superstructure, ships loading condition and hull form. In addition relevant openings are used, which may potentially decrease the angle of down flooding. This requirements makes it possible to use also so-called ‘demo projects’ for intact stability calculation that represent actual ships well enough for the hull form, loading condition and by the superstructure. The used NAPA in-build ‘demo projects’ are a bulk carrier and a naval frigate. The ice accumulation calculation is carried out also with the FLOODSTAND-B, which is introduced already in earlier chapters. These three example cases should describe the effect of icing rather well for different ship types.

The results include also two experimental studies. One of these experimental scenarios describe situation where ice accretion is 10 times higher than Polar Code defines (being 300 kg/m^3 for deck areas and 75 kg/m^3 for lateral projection). The other special case studies situation where icing occurs unsymmetrically, and only one side (port side studied in this case) of the ship is experiencing icing with the ice accretion values described in Polar Code. Aim of these experimental cases is to study more extreme icing scenarios that are still somewhat possible according to icing related literature and the probability of conditions exceeding these scenarios should be very small.

The example calculations use the basic IMO IS2008 criteria group, which is intended for all ship types, as test criteria to assess the effects of icing. The phrasing in the Polar Code requires that ‘...icing allowance shall be made in the stability calculations...’ which can be interpret so that icing needs to be considered in all relevant intact stability criteria for the ship in question. Since relevant criteria are different for different vessels, 11 basic intact stability criteria are selected for the example calculations. The intact stability criteria used are described in Table 7 below.

Table 7. Criteria used for intact stability calculations.

Name	Type	requirement
Area under GZ curve up to 30 deg	MINAREA	0.055 [mrad]
Area under GZ curve up to 40 deg	MINAREA	0.09 [mrad]
Area under GZ curve between 30 and 40 deg	MINAREA	0.03 [mrad]
Minimum GZ > 0.2	MAXGZ	0.2 [m]
Max. GZ at an angle > 25 deg.	POSMAX	25 [deg]
GM > 0.15 m	MINGM	0.15 [m]
Max. heel due to crowding of passengers	MAXHEEL	10 [deg]
Max. heel due to turning	MAXHEEL	10 [deg]
IMO weather criterion	Area ratio	1
HEEL < 16 deg	MAXHEEL	16 [deg]
HEEL < 80% of FRB immersion	MAXHEEL	Free board=<0.8 [deg]

5.1.1 Passenger ship FLOODSTAND-B

Passenger ship is interesting in respect of icing since they usually have large lateral projection area and large deck areas far away from sea surface. These lead to relatively large amount of icing since ice accretion is directly linked to exposed areas of the ship. The used ship model of FLOODSTAND-B is rather coarse for the modelling in the superstructure area, but has realistic projection area and highest deck. Some limitations are caused by the lack of balconies and more detailed sundecks that are supposed to partially extent on the three highest decks. Inputs used for the intact stability calculation of FLOODSTAND-B are presented in Table 8. As a remark, the reason why ships waterline length is greater in light loading condition is that the bulb is not completely submerged.

Table 8. Initial conditions and inputs for intact stability calculations due to ice accretion on FLOODSTAND-B.

	Light loading condition	**Heavy loading condition**
$L_{water\ line}$ [m]	227.1	220.86
$B_{water\ line}$ [m]	32.2	32.2
T [m]	6.90	7.4
Trim [m]	-0.069	-0.066
Heel [deg]	0	0
Displacement [ton]	32251.8	35367.1
CoG [m]	(99.73, 0, 15.44)	(99.48, 0, 14.90)
GM [m]	2.62	2.70
KG [m]	15.44	14.90
Immersion angle of freeboard [deg]	33.2	31
Criteria check	11/11 OK	11/11 OK
Decks locations [m]	Z=16, Z=19.8, Z =20.8, Z=39.8	Z =16, Z =19.8, Z =20.8, Z=39.8

As a result of using the intact stability tool for taking into account ice accretion, the effect of icing is shown in Table 9. Total amount of ice accumulated for lighter loading condition is 377.7 tons and the center of gravity foe this ice mass is located at X=101.73 m, Y=0.02 m and Z=29.88 m. For the heavier loading condition the values are respectively 375.9 tons and the center of gravity foe this ice mass is located at X=101.70 m, Y=0.02 m and Z=29.99 m.

Table 9. Results of icing on passenger ship.

	Light loading condition with ice accretion	**Full loading condition with ice accretion**	**Light loading condition with 10X larger icing**	**Light loading condition with unsymmetrical icing (P-side)**
T [m]	6.961	7.47	8.02	6.93
Trim [m]	-0.09	-0.09	-0.29	-0.08
Heel [deg]	0.0	0.0	0.1	1.1
Displacement [ton]	32629.5	35743.0	39144.1	32440.6
CoG [m]	(99.93, 0, 15.61)	(99.45, 0, 15.06)	(99.7, 0, 16.35)	(99.74, 0.05, 15.52)
GM [m]	2.39	2.49	0.77	2.51
KG [m]	15.61	15.06	16.35	14.98
Immersion angle of freeboard [deg]	33	30.9	30.8	33.1
Criteria check	11/11 OK	11/11 OK	9/11 OK	11/11 OK
Mass [ton] & CoG of ice [m]	377.7 tons at (101.73, 0, 29.88)	375.9 tons at (101.70, 0, 29.99)	3777.0 tons at (101.73, 0, 29.88)	188.8 tons at (101.73, 8.07, 29.88)

FLOODSTAND-B passed all studied criteria with both studied loading conditions where icing is considered as in Polar Code. The total mass of ice for this type and size of vessel is high, resulting GM value to decrease approximately 8.8% in case of light service loading condition, decrease of 7.8% in case of heavy loading condition. The loading conditions used corresponds closely to lightest service floating position and heaviest loading condition when draught is at deepest subdivision draught.

However ten times higher icing with light loading condition led to failing of two criteria studied, and is thus potentially dangerous for studied ship. The case of unsymmetrical icing did not pose danger for ship stability, only noticeable effect was the increase of heel from zero to 1.1 degrees, when comparing the result to actual icing scenarios that Polar Code defines. The list of criteria with required and attained values are shown in Appendix 4. The effect of icing can be seen also from the GZ curve figures below.

The GZ curves decrease clearly and the angle of vanishing stability, where GZ value goes to zero, decreases roughly 1.5 degrees. This applies for both loading conditions studied with the ice accretion values as in Polar Code.

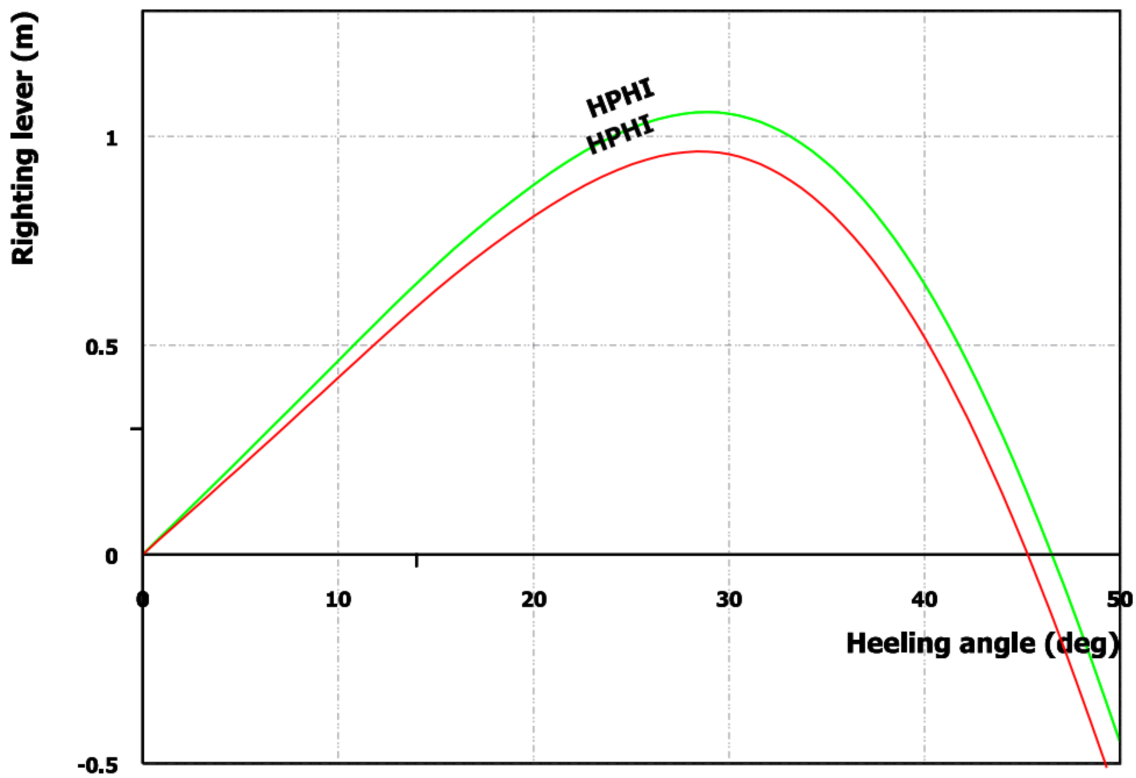

Figure 26. FLOODSTAND-B, GZ-curves of light loading condition with (red) and without icing (green).

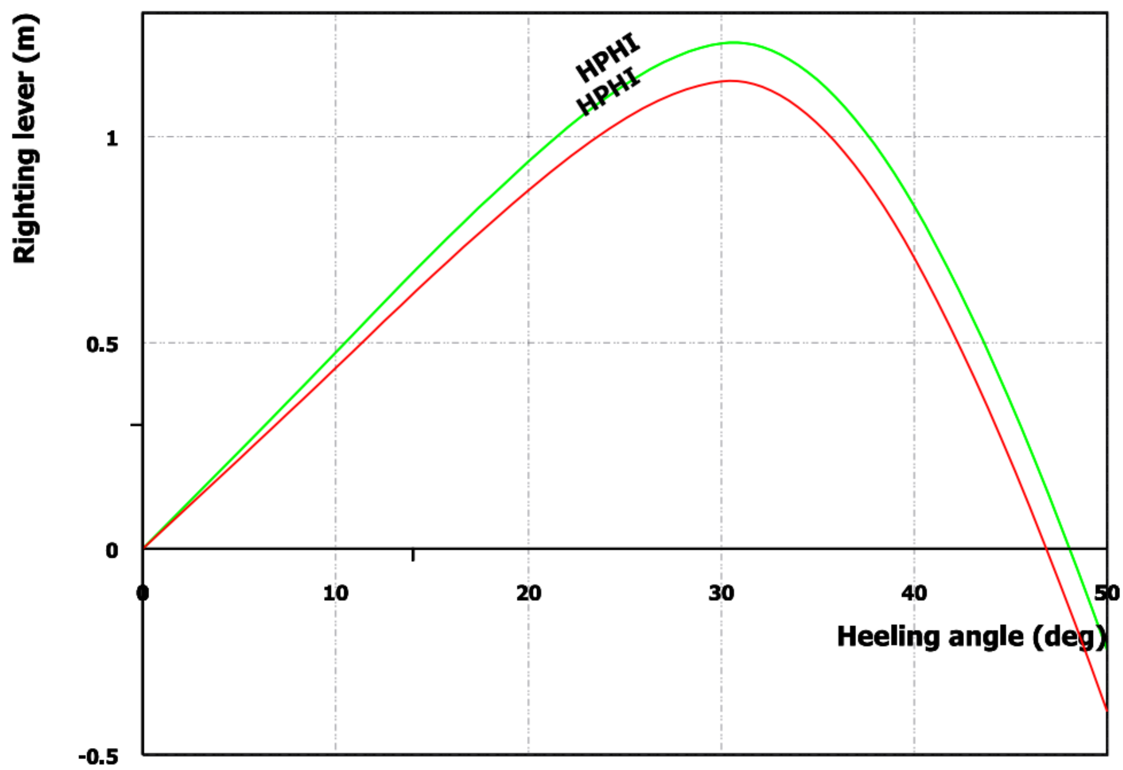

Figure 27. FLOODSTAND-B, GZ-curves of heavy loading condition with (red) and without icing (green).

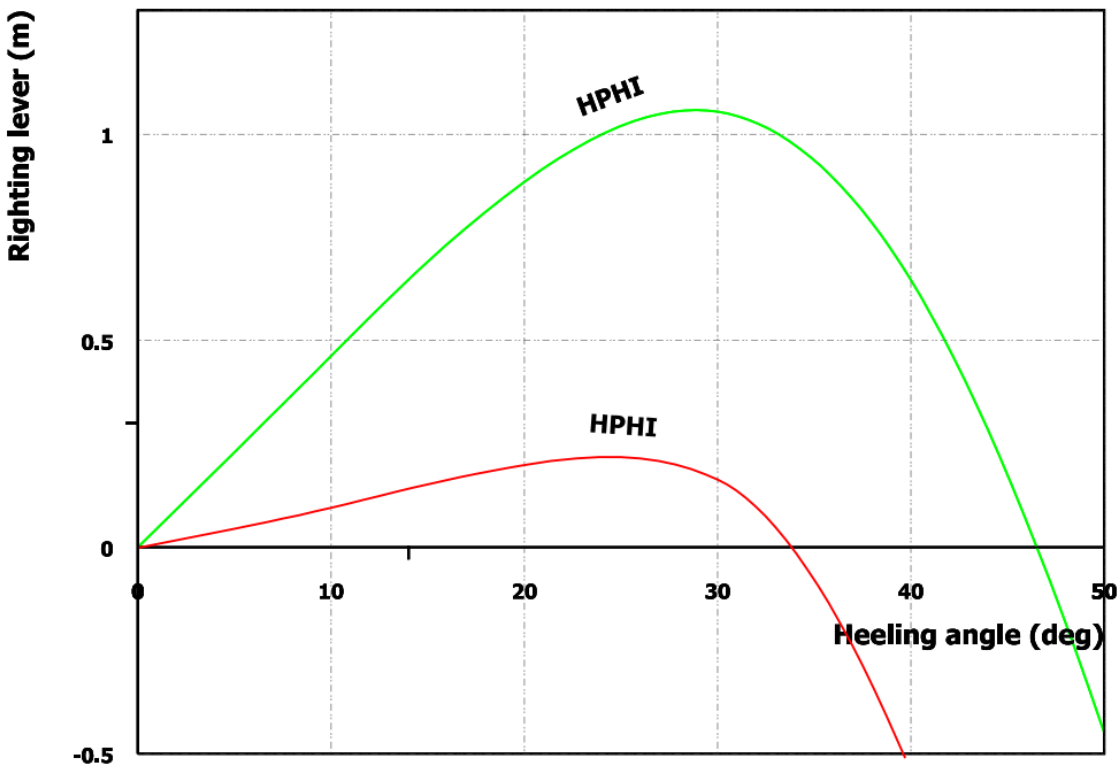

Figure 28. FLOODSTAND-B, GZ-curves of light loading condition with 10X higher icing (red) and without (green).

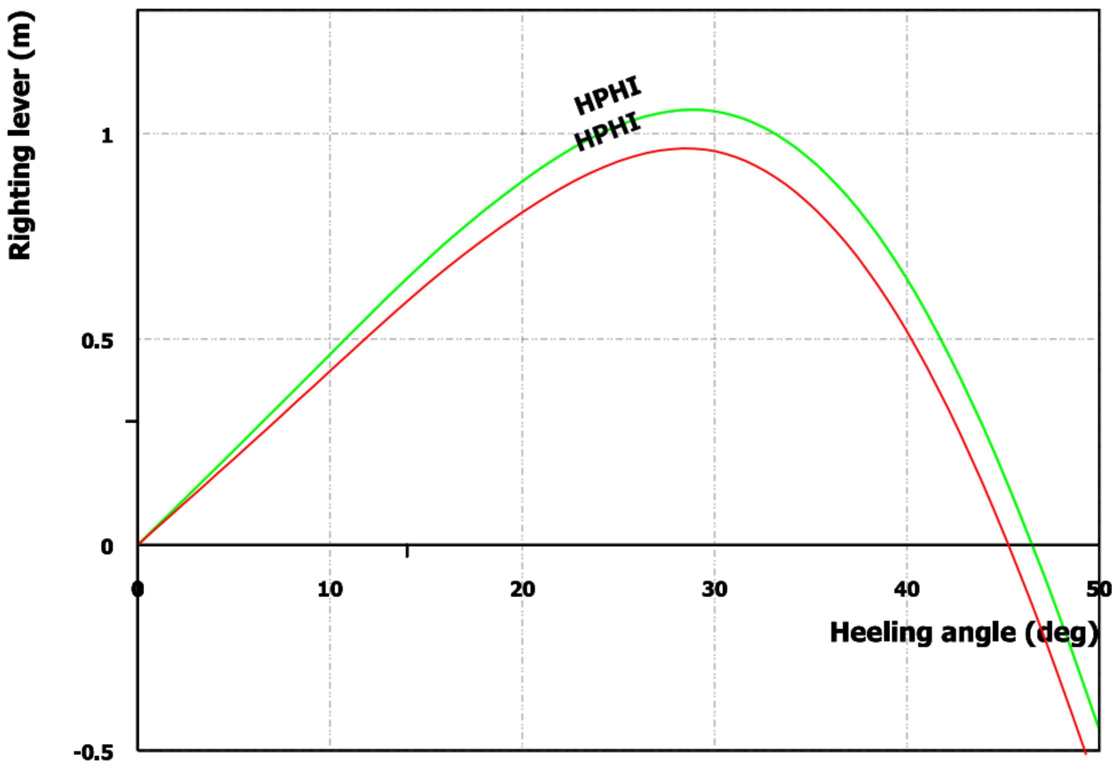

Figure 29. FLOODSTAND, GZ-curves of light loading condition with unsymmetrical icing (red) and without icing (green).

5.1.2 Bulk carrier

The cargo ship used for the example calculation is the one of the so-called demo projects included in NAPA software, describing a mid-sized bulk carrier. The main dimensions of the vessel and used inputs for intact stability calculation are in below Table 10.

Table 10. Initial conditions and inputs for intact stability calculations due to ice accretion on a cargo ship.

	Light loading condition	**Heavy loading condition**
$L_{water\ line}$ [m]	220.47	220.53
$B_{water\ line}$ [m]	36.00	36.00
T [m]	11.16	14.55
Trim [m]	0.92	4.10
Heel [deg]	3.9	2.9
Displacement [ton]	73466.5	98449.9
CoG [m]	(116.90, 0.66, 9.30)	(118.73, 0.39, 11.45)
GM [m]	3.76	3.69
KG [m]	9.30	11.45
Immersion angle (ope or FRB) [deg]	27.7	15.7
Criteria check	11/11 OK	11/11 OK
Deck locations [m]	Z=21.00, Z=23.50, Z=24.20, Z=25.00, Z=29.80, Z=35.40, Z=38.20	Z=21.00, Z=23.50, Z=24.20, Z=25.00, Z=29.80, Z=35.40, Z=38.20

The light loading condition represents light ballast loading condition and the heavy loading condition is the departure loading condition when all holds are full and ship is sailing with deep draught. The loading conditions are aimed to represent the extreme loading situations that are still expected to be used at sea, to reveal the effect of icing. However, the demo ship and its loading conditions do not necessarily represent completely realistic scenarios. Total amount of ice accumulated for the light loading condition is 268.9 tons and the center of gravity for this ice mass is located at X=105.50 m, Y=0 m and Z=21.91 m. For the heavier loading condition the values are respectively 257.2 tons and the center of gravity for this ice mass is located at X=105.23 m, Y=0 m and Z=22.45 m. The effects to floating position and stability related values after ice accretion are shown in Table 11 below.

Table 11. Results of icing on bulk carrier.

	Light loading condition with ice accretion	**Heavy loading condition with ice accretion**	**Light loading condition with 10X larger icing**	**Light loading condition with unsymmetrical icing (P-side)**
T [m]	11.19	14.58	11.44	11.13
Trim [m]	0.912	4.10	0.80	0.895
Heel [deg]	3.9	3.0	4.1	4.1
Displacement [ton]	73701.5	98671.3	75508	73289.6
CoG [m]	(116.87, 0.66, 9.34)	(118.70, 0.39, 11.48)	(116.5, 0.25, 9.64)	(116.87, 0.27, 9.27)
GM [m]	3.72	3.67	3.45	3.81
KG [m]	9.34	11.48	9.64	9.27
Immersion angle of freeboard [deg]	27.8	15.5	27	28
Criteria check	11/11 OK	11/11 OK	11/11 OK	11/11 OK
Mass [ton] & CoG of ice [m]	235.29 tons at (105.50, 0, 21.91)	221.30 tons at (105.23, 0, 22.45)	2352.9 tons at (105.39, 0.00, 21.90)	134.5 tons at (105.38, 9.00, 21.78)

The results reveal that icing has very little effect on the studied cargo ship, and all criteria are met in every studied icing scenario. Reason for this is that bulkers are designed to sail with very deep draught, but they can also sail with smaller draught when no cargo is loaded and ballast water is used to adjust the floating position.

In the case of light loading condition, GM value is decreased by approximately 1.1%. Using the departure loading condition where ship is fully loaded, the GM decreases 0.5%. Even the ten times larger icing does not have significant effect on draught, KG and GM values. Also the unsymmetrically accumulated icing do not have very large effect on the ship, as the ship has already heel in its original loading conditions. In fact the unsymmetrically located ice mass balances the ship in this case. The list of criteria with required and attained values are shown in Appendix 4. The effect of icing can be seen also from the GZ curve figures below.

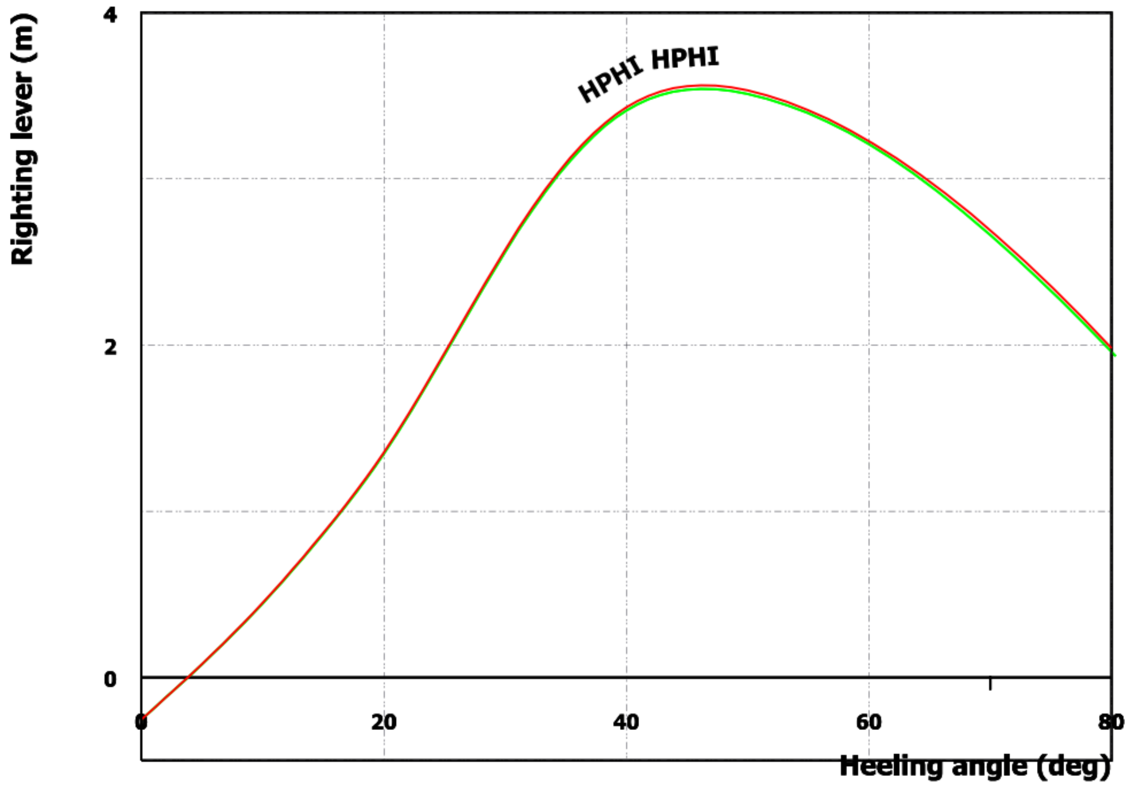

Figure 30. BULK CARRIER, GZ-curves of light loading condition with (red) and without icing (green).

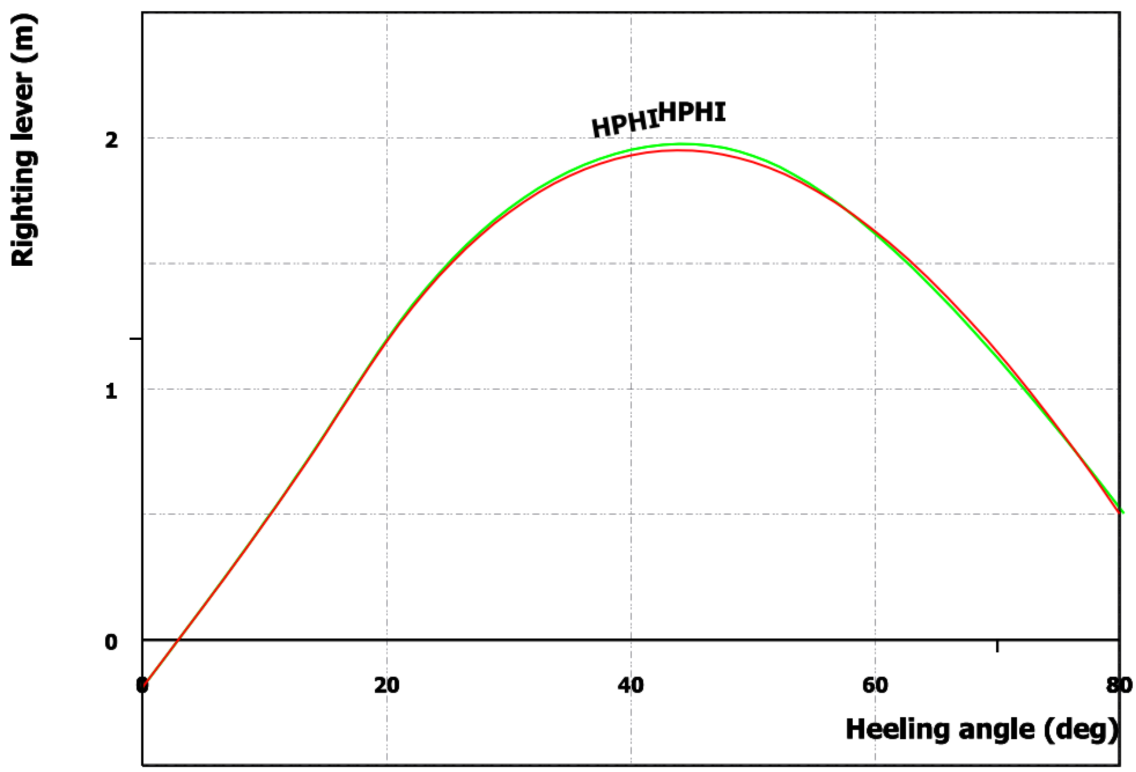

Figure 31. BULK CARRIER, GZ-curves of heavy loading condition with (red) and without icing (green).

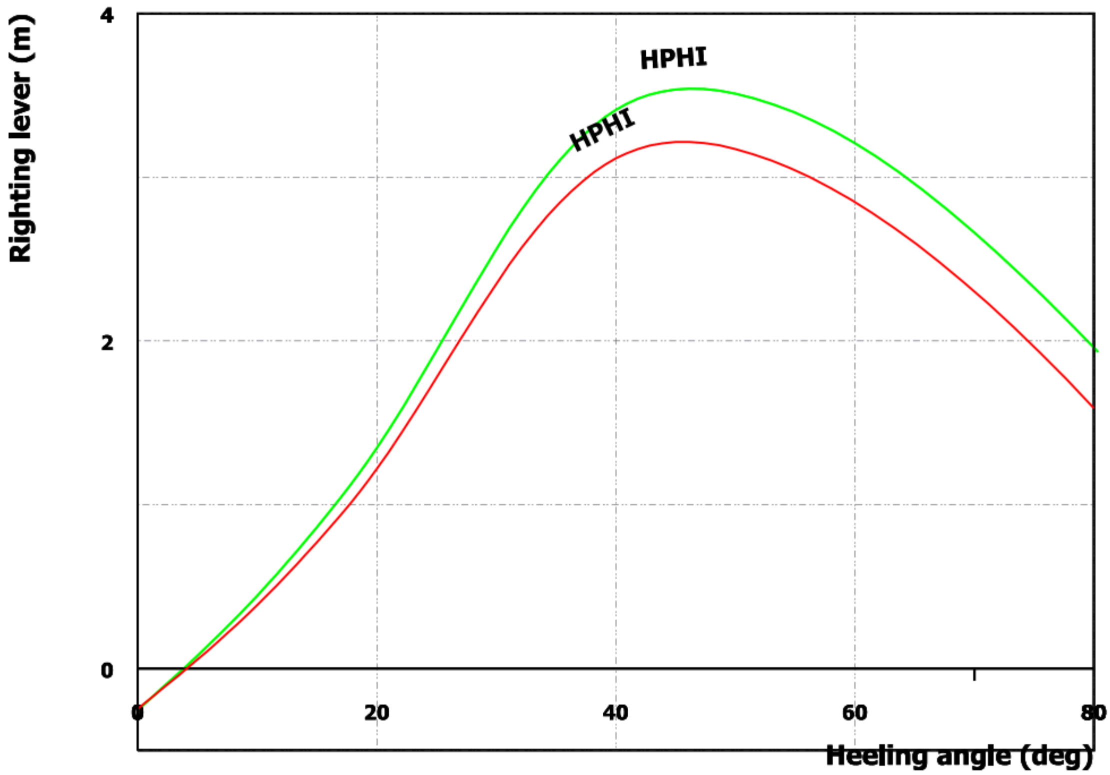

Figure 32. BULK CARRIER, GZ-curves of light loading condition with 10X higher icing (red) and without icing (green).

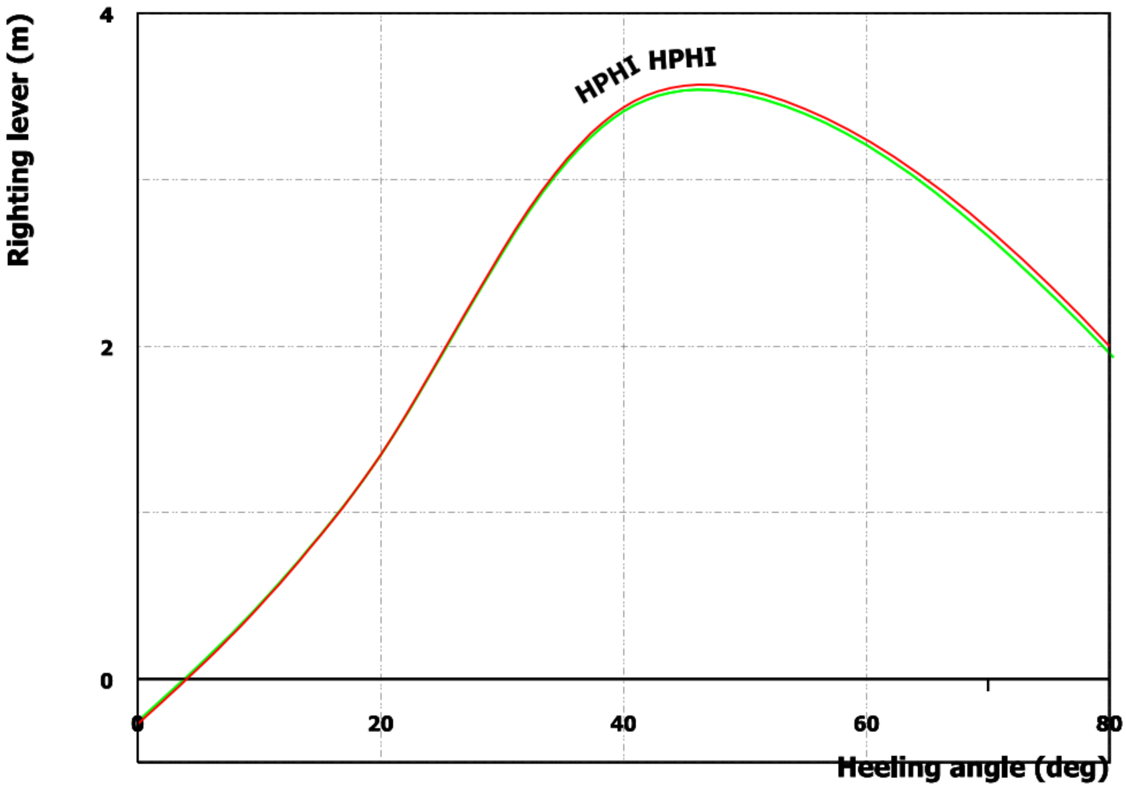

Figure 33. BULK CARRIER, GZ-curves of light loading condition with unsymmetrical icing (red) and without icing (green).

5.1.3 Naval frigate

The naval frigate used for this example calculation is also NAPA demo project. The main dimensions and floating positions of loading conditions of the vessel for criteria checks are shown in below Table 12. Naval vessels are designed usually with certain country specific naval rules, so studying the intact stability of such vessel with IMO criteria is in that sense not adequate. However, using here the IMO criteria provides indication about the effects of ice accretion and makes the comparison easier with other ship types.

Table 12. Initial conditions and inputs for intact stability calculations due to ice accretion on naval frigate.

	Light loading condition	**Heavy loading condition**
$L_{water\ line}$ [m]	136.85	138.00
$B_{water\ line}$ [m]	15.35	15.63
T [m]	4.01	4.460
Trim [m]	-0.815	0.116
Heel [deg]	0	0
Displacement [ton]	4070	4699.7
CoG [m]	(65.78, 0, 7.38)	(67.60, 0, 6.59)
GM [m]	0.28	0. 96
KG [m]	7.38	6.59
Immersion angle of freeboard [deg]	36.5	33.5
Criteria check	11/11 OK	11/11 OK
Deck locations [m]	z=9.40, z=12.40, z=15.40, z=16.40, z=18.40, z=21.40	z=9.40, z=12.40, z=15.40, z=16.40, z=18.40, z=21.40

The light loading condition represents light arrival loading condition and the heavy loading condition is the departure loading condition when the ship is sailing with deep draught. The loading conditions are aimed to represent the extreme loading situations that are still expected to be used at sea, to reveal the effect of icing. However, the demo ship and its loading conditions do not necessarily represent completely realistic scenarios. Total amount of ice accumulated for the light loading condition is 79.2 tons and the center of gravity foe this ice mass is located at X=56.39 m, Y=0 m and Z=10.84 m. For the heavier loading condition the values are respectively 78.3 tons and the center of gravity foe this ice mass is located at X=55.94 m, Y=0 m and Z=10.93 m. The GZ curves in below figures involving light loading condition show rapid increase of GZ value after about 30 degree heel. This is caused because the light loading condition that has very shallow draught and the hull form of the vessel. The hull form changes more rapidly closer to free board and leads to larger GZ as hull is wider The effects to floating position and stability related values after ice accretion are shown in Table 13 below.

Table 13. Results of icing on naval frigate.

	Light loading condition with ice accretion	**Heavy loading condition with ice accretion**	**Light loading condition with 10X larger icing**	**Light loading condition with unsymmetrical icing (P-side)**
T [m]	4.06	4.50	3.24	3.94
Trim [m]	-0.84	0.08	0.08	-0.73
Heel [deg]	0	0	34.3	9.3
Displacement [ton]	4149.2	4778.0	4862.4	4108.9
CoG [m]	(65.07, 0.00, 7.45	(67.42, 0, 6.66)	(63.80, 0.00, 7.94)	(65.15, 0.04, 7.41)
GM [m]	0.22	0.90	-0.20	0.25
KG [m]	7.45	6.66	7.94	7.41
Immersion angle of freeboard [deg]	35.5	32.2	29.8	35.7
Criteria check	7/11 OK	11/11 OK	1/11 OK	9/11 OK
Mass [ton] & CoG of ice [m]	77.8 tons at (56.10, 0.00, 10.70)	76.8 tons at (55.64, 0.00, 10.78)	777.6 tons at (56.10, 0.00, 10.70)	38.9 tons at (56.10, 4.35, 10.70)

The effect of ice on the superstructure decreases the GM values relatively large amount, but the absolute change in the GM values is approximately 0.05 meters for both loading conditions. In lightship loading condition, the GM value decreases 21.4% and in the heavier departure loading condition, the relative decrease of GM is 6.25%. The GZ curves reveal that the accumulated ice has rather significant effect on the ship stability, lowering the maximum GZ value around 20%. In addition, the angle of vanishing stability decreases a bit over 2 degrees. For the heavier loading condition, the effect of icing is smaller. GZ curve lowers around 6% and angle of vanishing stability is practically same as without icing.

Ten times larger ice accretion has tremendous effect on the stability of the ship in studied light loading condition, leading to failing in almost all criteria. Also the unsymmetrical icing leads to failing of three criteria with studied ship at light loading condition. The list of criteria with required and attained values are shown in Appendix 4. The effect of icing can be seen also from the GZ curve figures below.

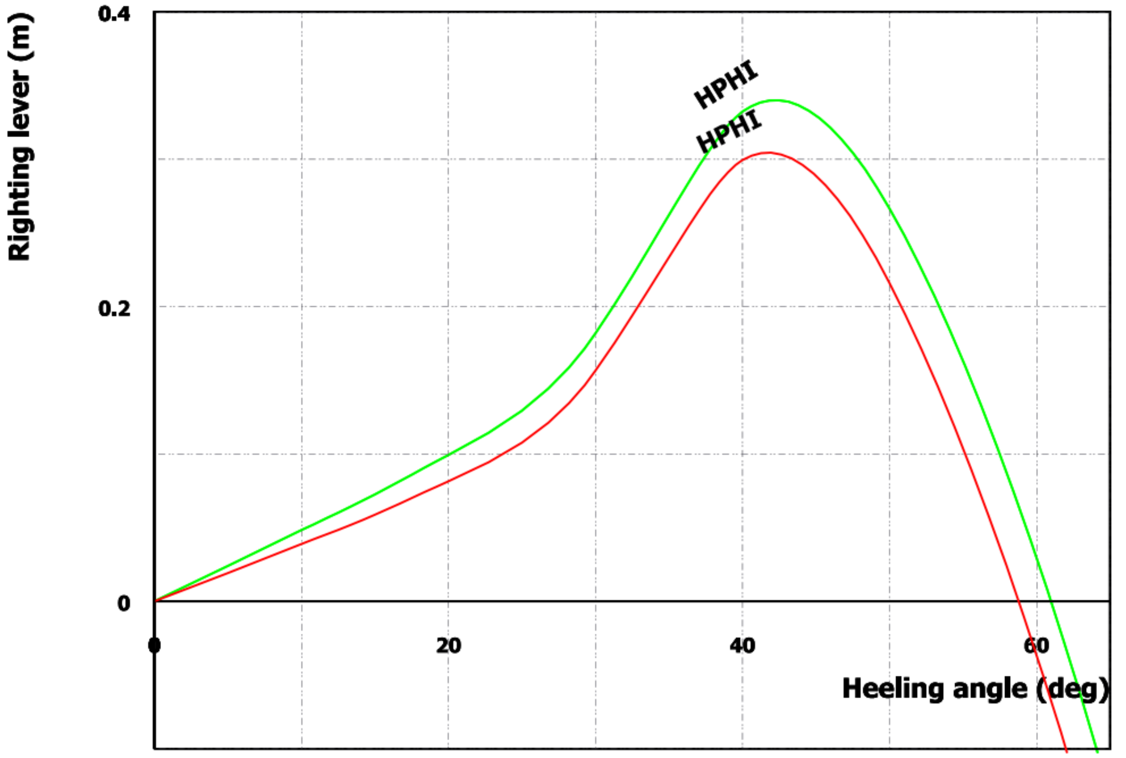

Figure 34. Frigate, GZ-curves of light loading condition with (red) and without icing (green).

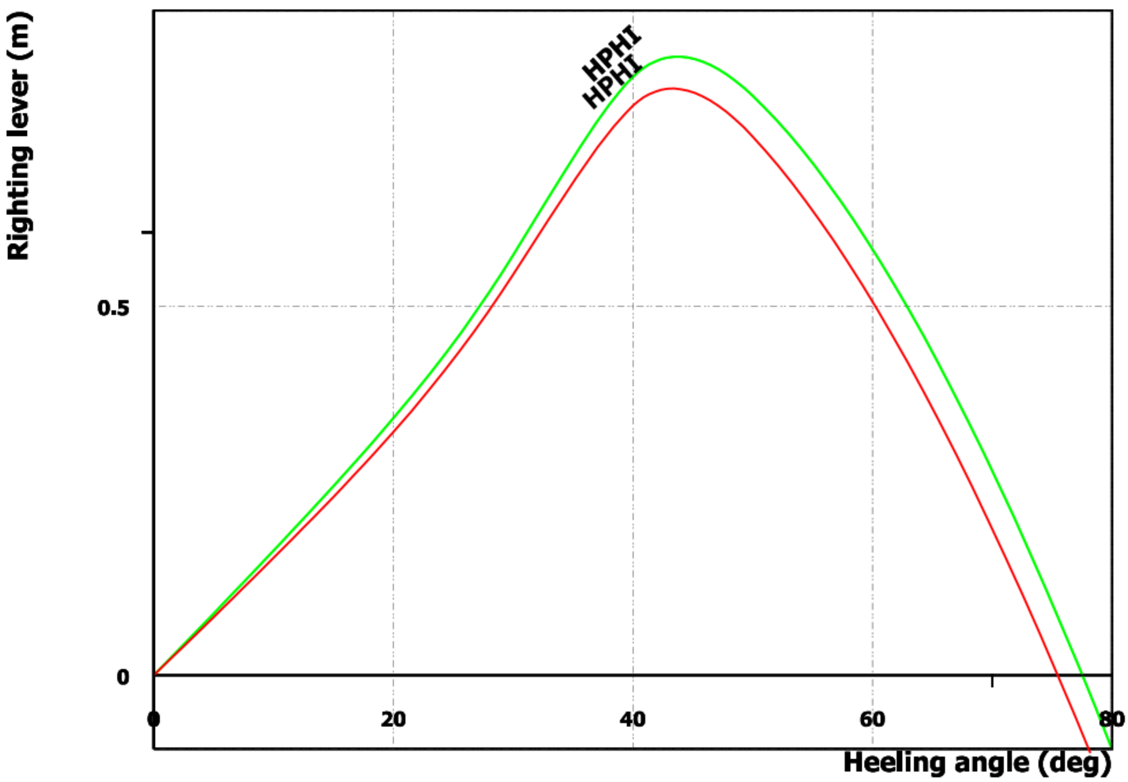

Figure 35. Frigate, GZ-curves of heavy loading condition with (red) and without icing (green).

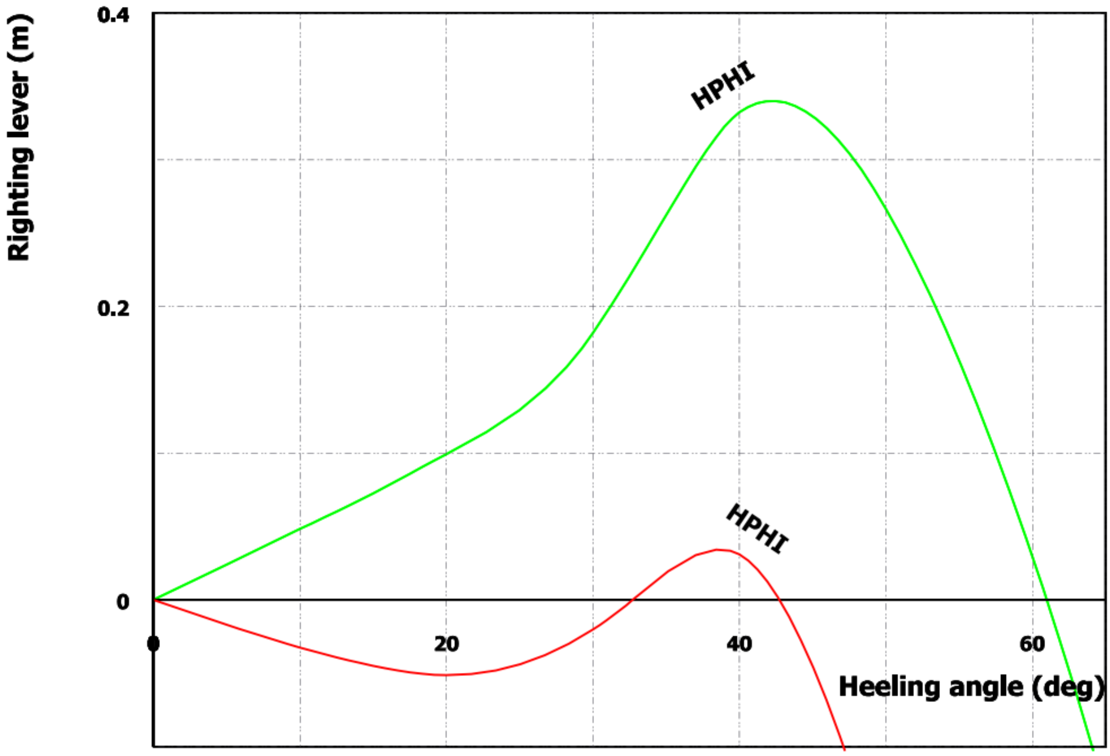

Figure 36. Frigate, GZ-curves of light loading condition with 10X icing (red) and without (green).

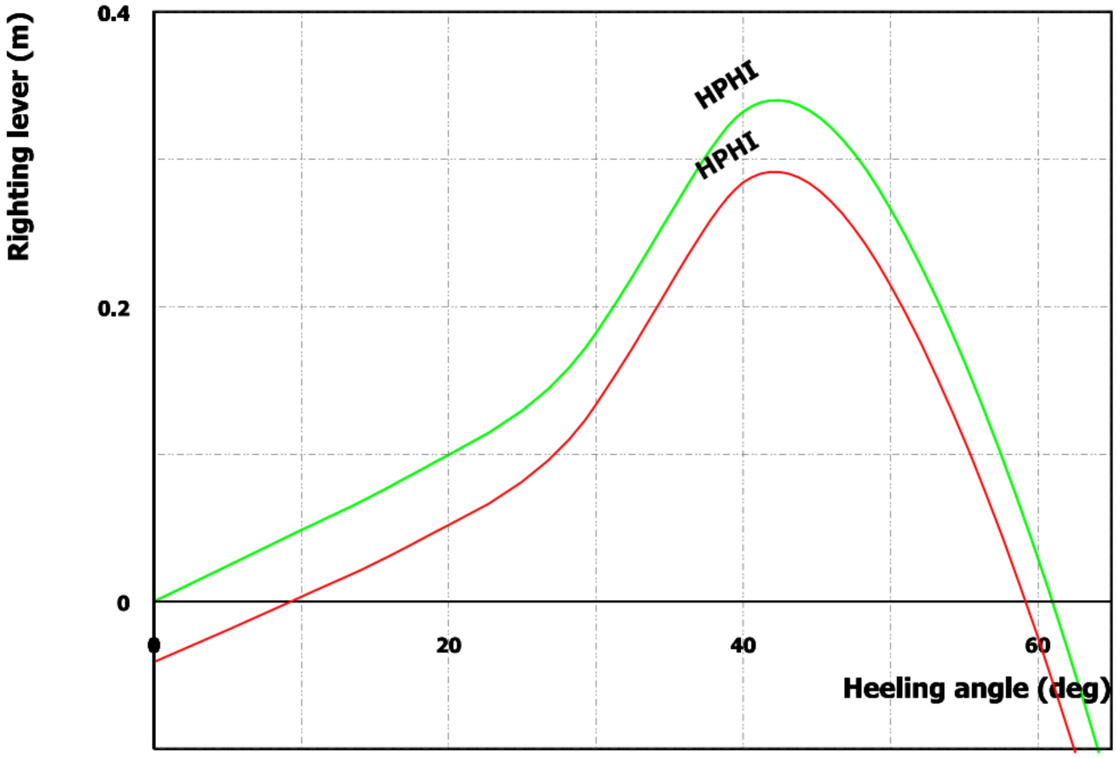

Figure 37. Frigate, GZ-curves of light loading condition with unsymmetrical icing (red) and without icing (green).

5.1.4 Example output of results produced with the tool

The detailed results of ice accretion on the studied three example ships are presented in sub chapters 5.1.1, 5.1.2 and 5.1.3. Example output of ice accretion results, produced by the developed tool, is shown in Figure 38. Complete output with criteria checks and the illustration of exposed decks and lateral projection, produced by the tool, and are shown in Appendix 5. The results show the amount of ice accumulated on superstructure's vertical areas as given in user input describing the Z-coordinate locations of the decks and other vertical areas. The results describe also the ice accumulated on ships' lateral projection. Illustrative figures describing the vertical areas and lateral projection are shown in Figures 39-41. It is worth noting again that the illustrative figures show the offset sections below the deck locations, meaning they do not represent the actual exposed area. Lateral projection in the figures showcase the projection as in lighter loading condition. For the actual results, these surface areas are taken account correctly as described in chapter 3.

Intact stability results

NAPA/D/LD/170510 DATE 2017-06-02
FLOODSTAND-B/A TIME 10:41
FLOODSTAND USER TIMO
1

##

Areas and CoG –locations of superstructure decks from lowest to highest.

Area at z-coordinate level 16 m is: 2333.15 m2 and CoG is (86.6323, 0.011074, 16) Area at z-coordinate level 19.8 m is: 307.816 m2 and CoG is (230.547, 0.530499, 19.8) Area at z-coordinate level 20.8 m is: 16.2606 m2 and CoG is (210.242, 0, 20.8) Area at z-coordinate level 39.8 m is: 6249.01 m2 and CoG is (97.4916, 0, 39.8)

Deck's CoGs (xyz) are 99.4513 0.0212361 32.8392 [m] and ice mass on decks is 267187 kg.

Area of the lateral projection above waterline is 13966.8 m2 for lightweight and 13741.2 m2 for polardeep, this number includes the areas for both sides of the ship.

For lighter LC (lightweight), lateral projections CoG (xyz) is 107.242 0 22.7204 [m] and the ice mass for lateral areas is 110512 kg including both sides of the ship. The lateral ice mass consists of 104751 kg from lateral projection, and 108727 kg that takes account discontinuous surfaces (as per Polar Code).

For heavier LC (polardeep), lateral projections CoG (xyz) is 107.243 0 22.976 [m] and the ice mass for lateral areas is 108727 kg including both sides of the ship. The lateral ice mass consists of 103059 kg from lateral projection, and 5668.23 kg that takes account discontinuous surfaces (as per Polar Code).

FINAL RESULT, ADDED TO SELECTED LOADING CONDITIONS (lightweight and polardeep): Combined center of gravity for ice masses is: FOR LIGHT LC lightweight : (X=101.731 , Y=0.0150225 , Z=29.8785) and the total ice mass is 377.699 ton. FOR HEAVY LC polardeep : (X=101.705 , Y=0.0150939 , Z=29.9865) and the total ice mass is 375.914 ton.

##

Figure 38. Example output produced with the tool, FLOODSTAND-B icing values for studied loading conditions.

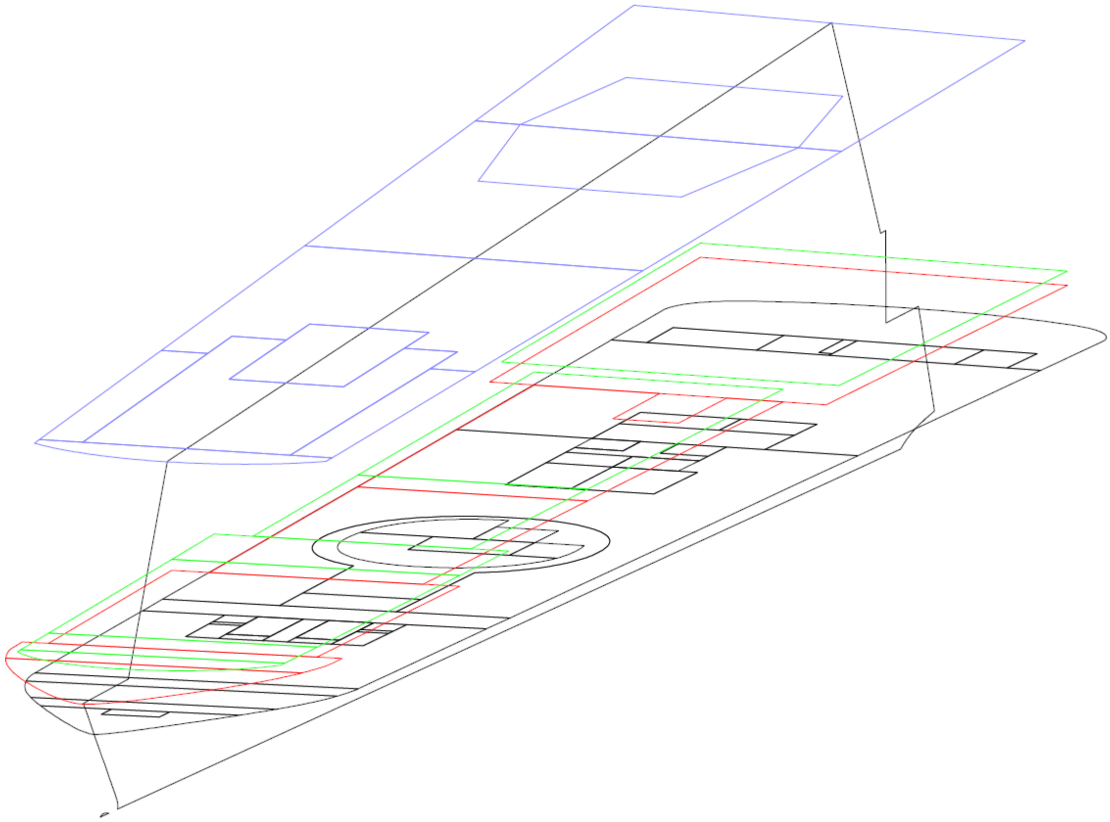

Figure 39. FLOODSTAND. Illustration of decks and side projection used in icing calculation, produced by the tool.

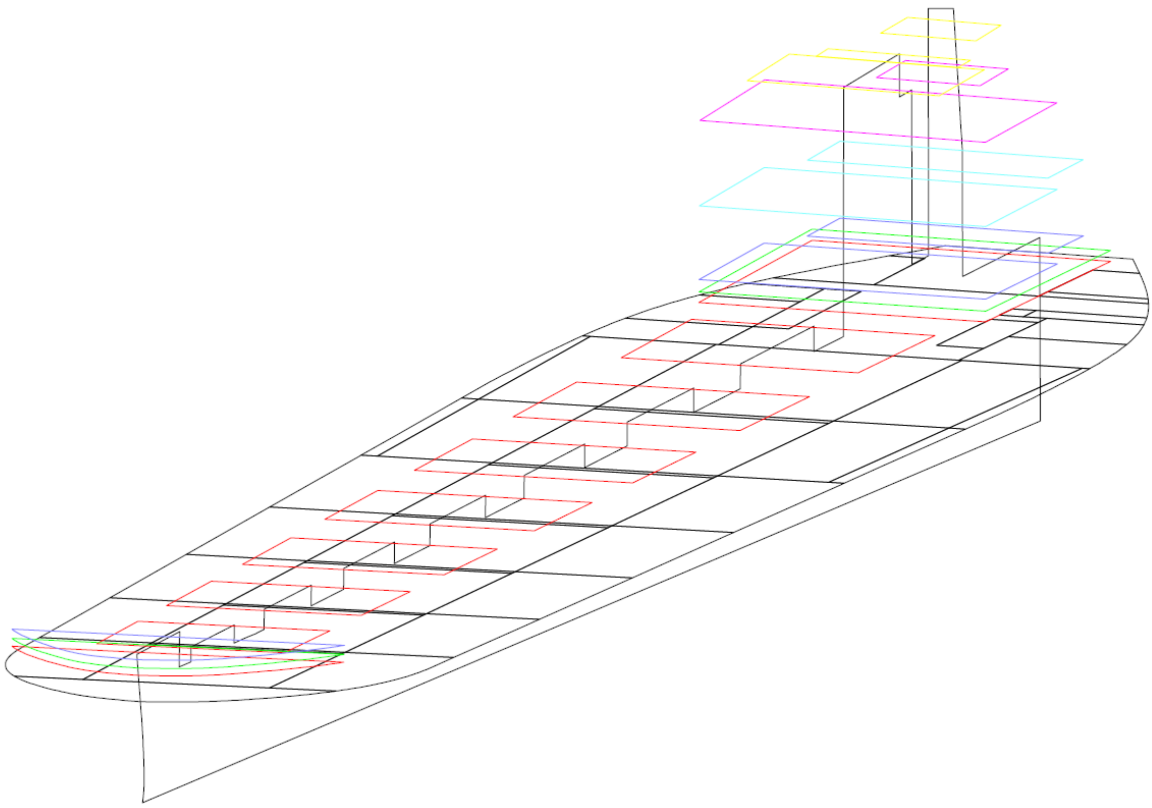

Figure 40. Bulk carrier. Illustration of decks and side projection used in icing calculation, produced by the tool.

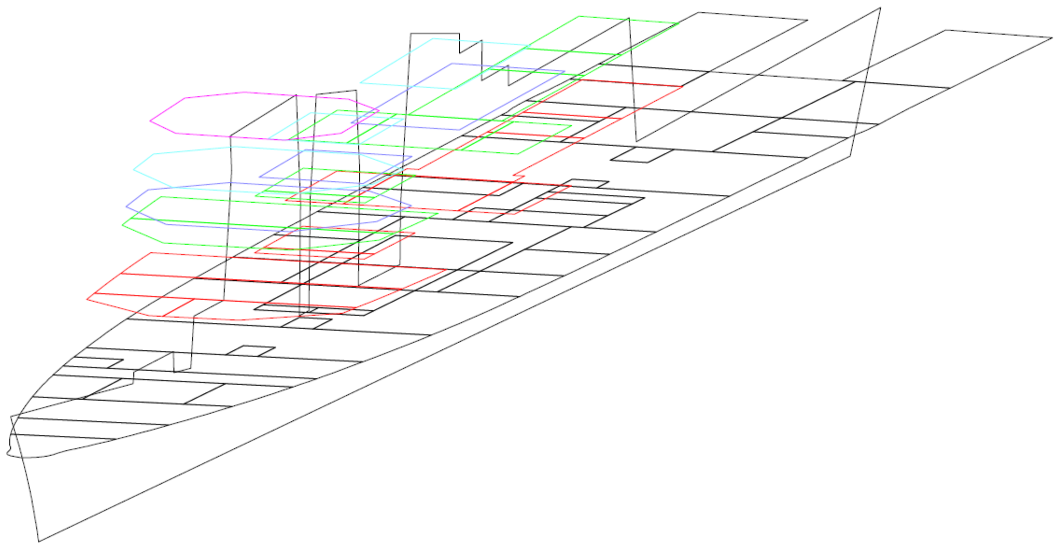

Figure 41. Frigate. Illustration of decks and side projection used in icing calculation, produced by the tool.

5.2 Damage stability

Damage stability results represent the effect of the deterministic damage scenario on 240 meter-long passenger ship FLOODSTAND-B. The FLOODSTAND-B is not originally designed with this type of stability requirement in mind but only according to SOLAS probabilistic damage stability rule. This subchapter contributes also by validating the usefulness of the developed tool. The ship model studied is the FLOODSTAND-B ship that was introduced in more detail under chapters 3 and 4.

The use of NAPA 'demo projects', as used in intact stability example calculations, are not adequate for damage stability study since they do not represent an actual ship project that is designed realistically to fulfill relevant regulations and is meant to be actually built. Using non-realistic ship model for the example calculations would lead to non-realistic results which could not be used for reliable analysis.

5.2.1 Passenger ship FLOODSTAND-B

The study of ice related damage stability has two main steps, which are: (1) identifying the relevant damage cases and then (2) the calculation of the required stability criterion. Identification of the relevant damage cases is carried out with the developed tool which follows the interpretation and damage dimension as introduced in chapter 2.4.2. The number of all potential one to three zone length damages with the FLOODSTAND-B is 1589, consisting of 558 port-side damages and 558 starboard-side damages, these numbers include also the potential relevant damages at bottom area. These values highlight the need for filtering tool to find at least most of the relevant cases. Below Table 14 presents how different filtering steps reduce the amount of damage cases towards the end of the filtering, revealing final relevant cases and. Last row in Table 14 shows the results of criteria check, which reveals 13 of the 240 relevant cases do not meet the criteria requirement.

The damage extents for the FLOODSTAND-B are 9.94 meters for damage length at fore area and 3.31 meter at aft area, and for the damage height 1.48 meters at fore area and 0.66 at aft area. The penetration value of 760 mm is set by an offset surface of the hull, which acts also as a limit for the damage generation so that no deeper damage cases is created. After the damage generation and filtering is carried out for both sides of the ship, total of 240 relevant damage cases if found which damage stability needs to be studied in respect to factor S_i. More detailed list of relevant cases found by the filtering is shown in Appendix 2.

Table 14. FLOODSTAND-B, damage case filtering and process of the tool.

	Port, side	**Port, bottom**	**Starboard, side**	**Starboard, bottom**
All possibilities	348	447	348	446
After offset/limit	251	346	269	297
After length filter	213	132	231	113
After height filter	141	77	141	96
After empty delete	141	77	141	96
After duplicate del.	83	35	81	41
Cases fulfilling criteria (R=1)	77/83 OK	35/35 OK	74/81 OK	41/41 OK

Explaining the function of the tool in more detail with port side damage cases, the first step of the tool generates the damages located on side area and removing damages below the double bottom, as the bottom area of the hull is processed later. After the damage cases that are having rooms below double bottom are removed and also cases that are more than the offset distance inside the ship, the number of cases to be filtered is decreased to 251. After the length filtering, the amount of relevant damage cases is reduced to 213, after which the height filter selects damage cases inside the limits of vertical extent, leaving 141 relevant damage cases. This number may still include empty and duplicate damage cases, depending how the subdivision table is created. Removing also the duplicates and empty cases, the final amount of relevant damages at port side is 141, meaning no empty cases were present in this case. Finally after removing the duplicate cases from the results, 83 relevant damage cases is left. These cases can be then used for damage stability calculation, however manual inspection of the damage cases is always recommendable before final statement can be done about damage stability.

Damages at the bottom area for starboard-side accounts at first 447 cases, decreasing to 346 after filter that removes cases that have rooms further away from the hull than 760 mm. Same damage length and height filtering as for side-area damages above, number of relevant cases decreases first to 132 and after height filter to 77. Finally removing duplicate and empty cases, leaves 35 relevant damage cases at port side bottom area.

In the scope of usefulness and reliability of the tool, most important goal is that all relevant cases, meaning the cases that are in accordance to Polar Code damage extents, are included in the results and none relevant case is left out. Secondary goal is that the resulted cases do not include irrelevant damage cases, since it is more laborious to search for more relevant cases manually than just leaving the irrelevant, but potentially harmless cases, in the results.

Manual study of the resulted damage cases revealed that the tool was able to find all possible damage scenarios, but the results included also some irrelevant cases. These irrelevant cases were mostly located below double bottom and having too large penetration value for being located below double bottom. Also some complex shaped room combinations having too high deck-spacing were included due to failing of damage-height filtering.

The damage stability calculation was carried out for the resulted damage cases. Inputs used for the stability calculation represented the deepest subdivision draught scenario and using subdivision, compartment connections and relevant openings as described in the study by Luhmann (2009) concerning the probabilistic damage stability of FLOODSTAND-B. **With these inputs, 13 (of the 240 relevant damage cases) damage case as defined in Polar Code lead to S_i index < 1**. This means that the studied passenger ship does not fulfill the Polar Code requirements for damage stability. Below Figure 42 shows damage case where the factor S_i reaches smallest value (being $S_i = 0$).

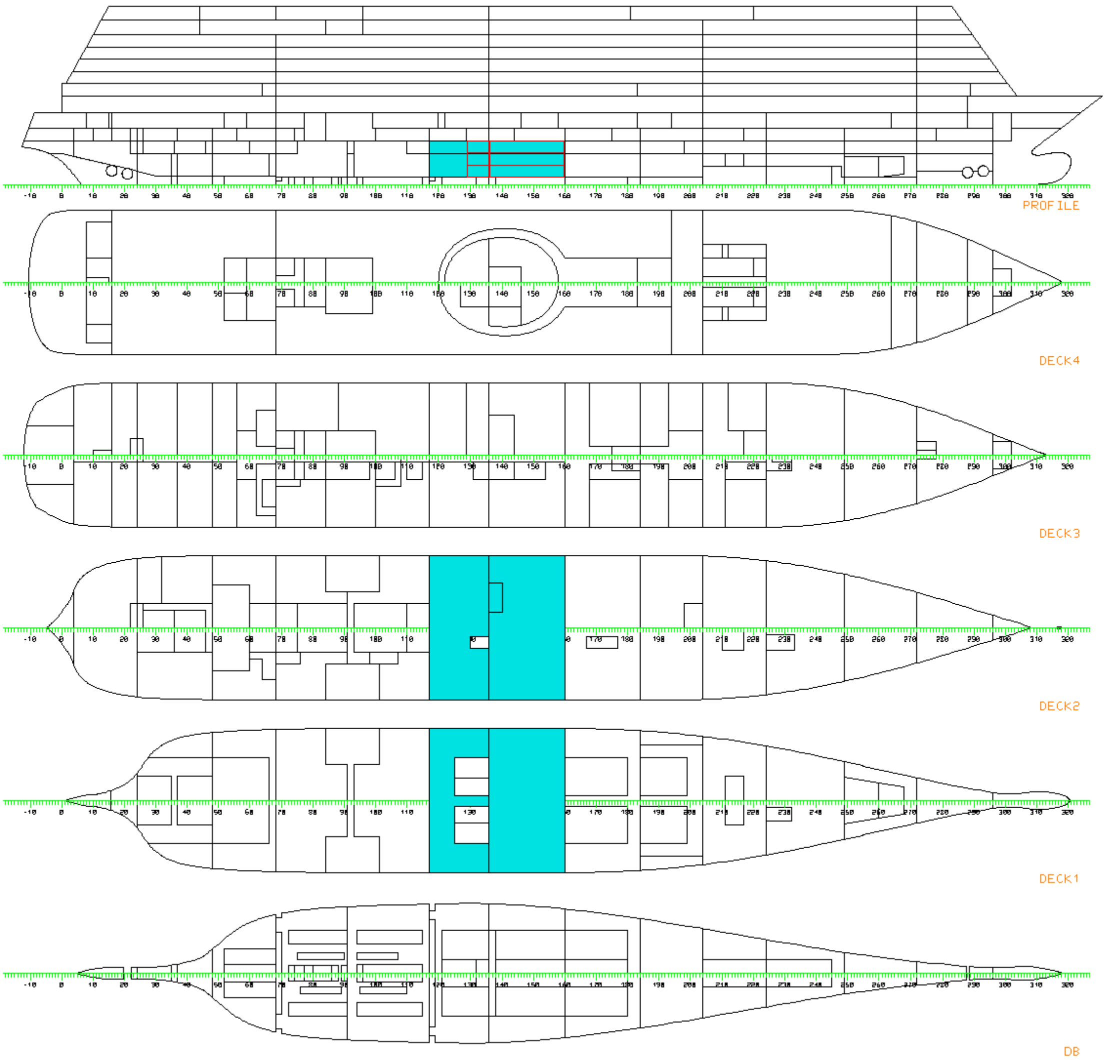

Figure 42. FLOODSTAND-B, damage case of smallest value of survivability factor

Summary of the critical damage cases by their type is presented in below Table 15. The table visualizes well, that most of the critical damage cases not fulfilling the criteria are two-zone cases, and that no three-zone cases fit in the limits of 'damage-box' defined by Polar Code with the studied passenger ship. Also most of the critical damages are two-zone damages, since naturally larger damages have larger effect on ship stability.

Table 15. Sumary of the damage cases not fulfilling the criteria by type.

	P-side	**P-bottom**	**S-side**	**S-bottom**
Critical dam. / 1-zone	2/30	0/17	0/29	0/19
Critical dam. / 2-zone	4/53	0/18	7/53	0/23
Critical dam. / 3-zone	0/0	0/0	0/0	0/0

With the studied passenger vessel eight of the failing damage scenarios were caused by one particular critical opening just above to the waterline level inside a large compartment. For example staircases in large compartments such as engine rooms are in this case easily leading to failing in the Polar Code criterion. The reason why these opening are critical is that they reduce the *range* value used in the survivability factor calculation and resulting small values for factor S_i.

6 Discussion

Intact stability

The intact stability requirement in Polar Code was found straight forward to implement as a tool for stability calculation. The results of ice accretion did not pose alarmingly direct danger for the used example ships apart from the naval frigate which was not
6.1 fulfilling some criteria in light loading condition. Passenger ship and bulk carrier passed all studied IMO criteria in heavy and light loading conditions.

The history of icing on ships and ocean structures is clearly recorded and studied. However the values used in the Polar Code for icing allowances are not very close to the extreme values that can occur in the polar waters, and represent rather modest ice accretion. This was supported by the interview of experienced naval architects who stated that several times higher ice accretion values have been used in the past for some ship designs due to classification society requirement, and considering the current Polar Code icing value to be rather low (Hovilainen & Vocke 2017). The history of the intact stability rule for icing may be one explaining factor, as the rule was originally defined for fishing vessels.

Studying the stability of the example ships with 10 times larger icing values revealed that the studied passenger vessel and naval frigate failed to fulfill the used stability criteria. Higher icing values were not as critical for the studied bulk carrier.

The studied scenario of uneven icing (port side icing only) revealed that it is not more critical scenario for the studied passenger ship and bulk carrier, as all criteria were fulfilled. The studied naval frigate showed that unsymmetrical icing is actually leading to less failures with the studied criteria, compared symmetric icing as Polar Code defines.

This study provided evidence that there is potential need for reviewing of the intact stability rules in Polar Code. It is at least suspicious that same icing requirements are used similarly for large cargo ships and passenger vessels, as originally intended for fishing vessels. However the difference in ship sizes and purposes is not a major concern. The main reason for the potential need for reviewing the intact stability rules lies in the full-scale measurements of icing of actual icing incidents and also in the statements provided by the arctic ship designers.

Last aspect worth noticing is the assumption of symmetrical and even icing of ship structures. More likely and extreme scenarios would be that only one side of the ship or that only bow area experiences icing, resulting a larger shift in the location of center of gravity compared to situation without icing. Even though the results showed that the difference is not large or between symmetric and unsymmetrical icing, different options for icing consideration could be worthwhile to study further, including as realistic scenarios as possible.

6.2 Damage stability

Damage stability requirements in Polar Code proved to be a bit unclearly defined. The background of the damage extents remained partially unsolved as no thorough explanation was to be found for the extent values.

An educated guess and reasoning led to a conclusion that the damage length and vertical height are derived from accident kinematics, based on which it can be roughly assumed that larger ship with more mass (and thus more kinetic energy) results larger damage. The damage penetration value remained unsolved. Only hint comes from the value itself being uneven for metric system. This indicates to the time before year 1974, when for example SOLAS convention still used imperial units. As a penetration value due to ice impact, the 760 mm is seen to be adequate, even though the reason for the selection of such value is not completely clear (Hovilainen & Vocke 2017).

Interpretation of the shape of the ‘damage-box’ is not stated clearly in the Polar Code. Especially the hull areas where hull has curvature causes problems when setting the limits for the damage box. Another unclearly defined part of the rule is how to interpret the damage extents at bottom area. This study offered on way of interpretations for these issues, as no official statements were available at the time. The selected interpretation was chosen since it can be implemented ambiguously for all hull areas and is simpler for the developed tool to be used in the damage case filtering.

As damage stability regulation concerns only new-builds, the damage stability requirement does not directly cause difficulties for existing ships to gain the Polar Ship Certificate as it can be taken into account in the design phase as any requirement affecting the ship structures. For new-builds, the rule concerns more precisely only A and B category ships, for which design the damage stability requirement should not be major obstacle. For example the use of double sides in addition to double bottom should effectively prevent critical damages in respect to ship stability (Hovilainen & Vocke 2017).

The damage stability case study revealed that the studied 2009 SOLAS passenger ship does not survive from all damage scenarios that Polar Code requires to take into account. 13 of the 240 relevant damage cases did not pass the criteria check where requirement for survivability factor is $S_i = 1$. The result suggest that the existing ships following SOLAS 2009 probabilistic damage stability criteria are potentially vulnerable for such damage scenarios as Polar Code defines. This suggests also that new-build category C ships are also potentially vulnerable for such damage scenarios as defined by Polar Code.

The new-builds in Polar Code category C, and other vessels having IACS ice class lower than PC-7 are in greatest danger of having catastrophic ice damage. Even though some of the category C ships are not even intended to be sailed at sea areas where ice is present, bits of ice can drift away from glaciers and ice sheets, which is a risk also for category C ships having lower ice class below PC-7. The accident cases of MS Finnpolaris and MV Explorer highlights the danger of multi-year that might difficult to notice in bad weather conditions or in darkness, even if the ship has proper ice class.

Since the damage extents due to ice impact are in relation to the ship mass and speed, one way to reduce the effects of collision would be require lower speeds at areas where ice may occur. Another way is naturally to build ships with higher ice class, this may not be always solution since also category C ships will most definitely exists, and also other existing ships with inferior ice class. Thus lowering speeds at higher-risk areas would be easy to implement especially for passenger ships where many lives are at risk and the need for time saving is lesser than with cargo ships. However it does not remove the risk for a ship sailing too fast for example by human error and colliding with ice. Currently the concept of lowering speeds is implemented in the IACS guidelines for artic shipping but not as a requirement (LBMA 2009). Thus making it mandatory for category C ships would be worth considering and studying more.

7 Conclusion

Polar Code is a goal orientated set of rules for ships intended for Arctic and Antarctic operations. The methods how to achieve the goals, are left mostly for the ship designer to decide. The stability related rules are one of the most accurately defined rules in Polar Code, having exact values for ice accretion and damage extents, compared to some other requirements that require to *consider* certain aspects of ship design, leaving more room for interpretation.

In the damage stability rule the shape of the 'damage-box' applied on ship, to describe the ice related damage, has room for interpretation. One aspect not mentioned in the rules is should also different floating position be studied when locating the damage scenarios, as for some ships trim can vary significantly in different operations. Also the rules does not state should the icing and damage scenarios be studied when occurring at same time. Since the simultaneous situation is not mentioned, it can be understood that it is not necessary, however source was found guiding to study both scenarios at same time. This may be something were different classification societies or authorities have their own requirements.

As no official interpretation for damage extents and shape was to be found available, this study offers one solution. In short, damages transversal penetration is limited to an offset surface located at 0.76 meters from hull inwards, and damage extents are limited to this surface perpendicularly to longitudinal axis of the ship. At bottom area the damage's vertical height is measured in transversal direction, as the vertical height is at those areas limited to the offset surface.

Both stability rules should represent a realistic scenario that may pose danger for ship stability. From sensibility point-of-view, meaning what kind of operational situations the requirements describe, the study suggests that Polar Code does not represent extreme situations or sea conditions. For the intact stability requirement even higher ice accretion values could be seen justified. Even though the current way defines icing to be considered on high locations where icing should be minimal, making the rule more conservative. The damage extents in the rule concerning ships damage stability, are seen adequate. The only concern is that the requirement does not include category C ships, as it would be major accident if passenger vessels of category C would encounter severe collision with piece of multiyear ice. Also more extreme interpretation would include both icing and damage scenario to be occurring at same time.

The partial goal of the study was to develop tools to account ice accretion and to find the relevant damage cases as Polar Code defines the situation. The tool development achieved its goals, enabling the case studies of intact and damage stability for example ships. The intact stability tool achieved very good results as manual verification of the results in development phase were found to be correct. As a tool, the intact stability tool is very simple by its functioning, as it takes planar sections of the deck and calculates areas and center of gravity -locations of each exposed decks and also from the lateral projection of the ship. The simple geometrical 2D approach decreases the possibility of errors, as amount of special or complex situations is limited.

The tool for identifying the relevant damage cases proved to work correctly in development phase with simple test-case ship model. However it was noticed that real ships having more complex compartment geometries are practically impossible to take account correctly. The tool developed in this time-frame of the study was found to be able to found the relevant damage cases, but still some irrelevant cases were included in the results.

Both tools proved to work as a good help for a ship designer, making the process more efficient, but still some work is left that the tools cannot do, especially in the case of identifying the relevant damage cases having several compartments with complex shapes. However in most cases the effects of icing and ice related damages could be studied with the help of these tools, creating the situations as Polar Code requires.

The effects of icing did not cause loss of stability for studied passenger vessel or bulk carrier. However naval frigate did not fulfill all stability criteria when it was studied with in light loading condition and ice accretion. As naval ships are not designed solely according to IMO rules, the result does not indicate directly, should the effect ice accretion be accepted or not. Still, a conclusion can be made that smaller vessels are more vulnerable for icing than larger ships, as the studied naval ship is smallest of the three ships studied, being at 140 m in length, compared to the bulker (220 m) and the passenger ship (240 m). The conclusion is also supported by literature, were the icing was most critical for small fishing vessels at typical size of 100 m in length. Using 10 times larger values for ice accretion the results revealed that the studied passenger ship and naval frigate were failing in some of the intact stability criteria studied. However it can be argued how reasonable it is that a 240 meter-long passenger ship will have 30 cm thick layer of ice on all exposed deck areas and 8 cm of ice on lateral areas. The study of uneven icing indicated that such situation is not clearly more critical for any of the ships studied, supporting thus the validity of the current ice accretion definition in Polar Code.

The effect of damage stability was studied only with a 240 meter-long passenger vessel, designed already in 2009. The number of case studies was limited since as it was found difficult to obtain several realistic ship models. However the studied ship was one of the most interesting, since it is quite average-sized and single hull, describing rather well typical expedition ship. The study aimed to reveal how capable existing ships are under the deterministic damage scenario as defined in Polar Code. The passenger ship failed to meet the damage stability criteria on 13 of the 240 relevant damage scenarios, meaning the studied ship would not fulfill the Polar Code requirement.

As a conclusion, existing ships or category C ships are possibly vulnerable for the damage scenario defined in Polar Code. Following only SOLAS 2009 requirements in polar ship design for new ships, may lead to difficulties when gaining Polar Ship Certificate. Especially openings in the compartments close to waterline are potentially critical. The interpretation of polar code is still somewhat unclear as there is very limited amount of official documentation for interpretation or example cases available. The identification of the state of Polar Code is also one major outcome of the study, suggesting there is still work in the future to clarify the requirements for ship builders and the industry.

As for future work, there exists also possibilities for improving the tool to identify the relevant damage cases. For example topology-based approach could be applied for identifying the relevant damage cases. This would enable better filtering accuracy for complex-shaped rooms since the actual geometry of rooms is applied directly to study does the ‘damage-box’ fit inside in the damaged compartments, and is it forming a subset of those compartments which would include parts of all compartments involved. For the rule clarification most important would be to define how the damage extents should be measured, explaining also why the normal direction is applied for penetration value.

Part of the future work would also to study the effects of ice related damage stability requirements of the Polar Code with some 3D ship model of actual existing ship. This would provide more solid evidence on the matter of safety of existing and category C ships in polar waters. Also statement should be made, does both intact and damage stability requirements need be taken into account at same time. Also the suggested idea of decreasing speeds of passenger vessels at areas with higher probability of ice, could be worth studying more in the future.

With these results and presented back ground of research and older rules, the stability related chapter of the Polar Code appears to be somewhat adequate set of rules for vessels sailing in polar areas, but is also found to be partly unclear and not thoroughly explainable, about on what the requirements are based on. The design values used for ice accretion on ship structures can be considered to be not very conservative with the evidence presented in this study. Also the interpretation of the damage dimensions orientation would benefit from more detailed explanation in the rule text.

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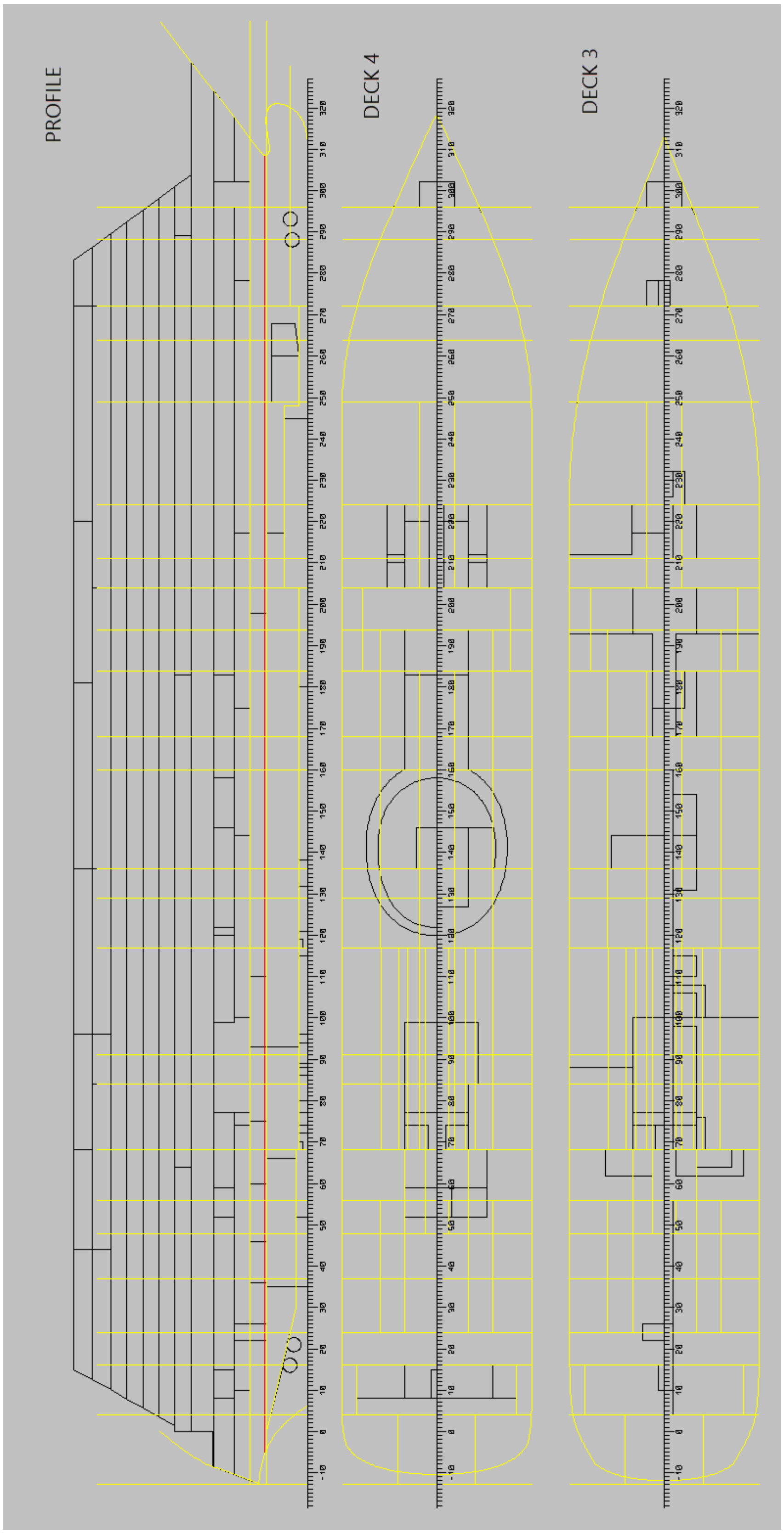
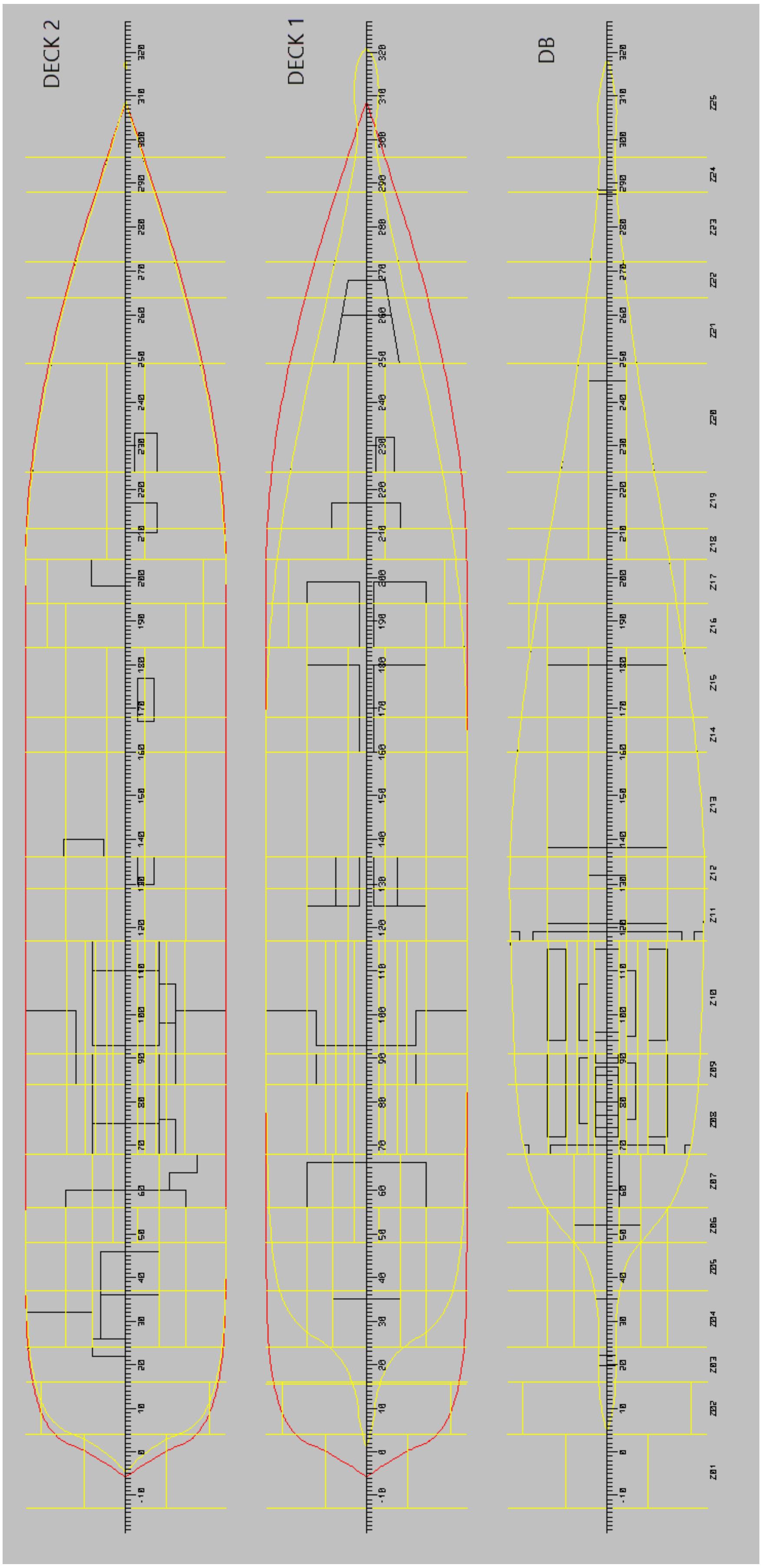
List of appendices

Appendix 1. FLOODSTAND-B, Subdivision.




DECK 2
DECK 1
DB

Appendix 2. Damage stability calculation results for example ship FLOODSTAND-B

CASE: DS represents the used loading condition, in which ship is floating at designed subdivision draught.

RANGESOL: Range from zero-heel to immersion of first relevant opening per SOLAS

HEEL: Heel of the ship at equilibrium after damage

GZMAXR: Maximum GZ from equilibrium to flooding

GZMAXS: Maximum GZ for s factor calculation

SFACSOL: S factor by SOLAS II-1

STAT: Status of stability criteria (OK/NOT MEET)

OPEN: Critical opening

Port side results, including side and bottom area damages.

CASE	RANGESOL deg	HEEL deg	GZMAXR m	GZMAXS m	SFACSOL	STAT	OPEN
DS/POLARDAMP2.1.2-1	16.0	0.0	0.86	0.10	1.0000	OK	ST23-1
DS/POLARDAMP2.2.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/POLARDAMP2.2.2	16.0	0.0	0.87	0.10	1.0000	OK	ST23-1
DS/POLARDAMP4.1.3-2	16.0	0.3	0.89	0.10	1.0000	OK	ST33
DS/POLARDAMP5.1.3-2	16.0	0.2	0.91	0.10	1.0000	OK	ST33
DS/POLARDAMP6.1.2-1	16.0	0.0	0.91	0.10	1.0000	OK	-
DS/POLARDAMP6.1.3-2	16.0	0.0	0.89	0.10	1.0000	OK	-
DS/POLARDAMP8.1.2-1	16.0	0.0	0.94	0.10	1.0000	OK	HEW5-1
DS/POLARDAMP8.1.3-1	16.0	0.1	0.86	0.10	1.0000	OK	ST53S
DS/POLARDAMP8.1.3-2	16.0	0.0	0.89	0.10	1.0000	OK	ST53S
DS/POLARDAMP9.1.2-1	16.0	3.9	0.79	0.10	1.0000	OK	-
DS/POLARDAMP11.1.2-1	16.0	0.0	0.94	0.10	1.0000	OK	HEW6
DS/POLARDAMP11.1.3-1	16.0	0.0	0.85	0.10	1.0000	OK	ST73
DS/POLARDAMP11.1.3-2	16.0	0.0	0.85	0.10	1.0000	OK	ST73
DS/POLARDAMP12.1.2-1	16.0	0.0	0.90	0.10	1.0000	OK	-
DS/POLARDAMP12.1.3-1	16.0	0.0	0.79	0.10	1.0000	OK	ST83
DS/POLARDAMP12.1.3-2	16.0	0.0	0.86	0.10	1.0000	OK	ST83
DS/POLARDAMP14.1.2-1	16.0	0.0	0.90	0.10	1.0000	OK	-
DS/POLARDAMP14.1.3-1	0.9	0.0	0.03	0.03	0.0000	NOT MET	ST93
DS/POLARDAMP14.1.3-2	4.1	0.0	0.12	0.10	0.7094	NOT MET	ST93
DS/POLARDAMP16.1.2-1	16.0	0.0	0.87	0.10	1.0000	OK	-
DS/POLARDAMP16.1.3-1	16.0	0.0	0.74	0.10	1.0000	OK	ST103
DS/POLARDAMP16.1.3-2	16.0	0.0	0.83	0.10	1.0000	OK	ST103
DS/POLARDAMP21.1.1	16.0	0.0	1.03	0.10	1.0000	OK	-
DS/POLARDAMP21.1.2-1	16.0	0.0	0.93	0.10	1.0000	OK	-
DS/POLARDAMP21.1.3-1	16.0	0.0	0.80	0.10	1.0000	OK	ST133
DS/POLARDAMP21.1.3-2	16.0	0.0	0.85	0.10	1.0000	OK	ST133
DS/POLARDAMP22.1.3-2	16.0	0.0	0.90	0.10	1.0000	OK	-
DS/POLARDAMP3-4.1.1	16.0	1.6	0.90	0.10	1.0000	OK	-
DS/POLARDAMP3-4.1.4-4	16.0	0.9	0.78	0.10	1.0000	OK	ST33
DS/POLARDAMP4-5.1.1	16.0	1.6	0.89	0.10	1.0000	OK	-
DS/POLARDAMP5-6.1.1	16.0	1.6	0.94	0.10	1.0000	OK	-
DS/POLARDAMP5-6.1.3-3	16.0	0.4	0.84	0.10	1.0000	OK	ST33
DS/POLARDAMP6-7.1.1	16.0	0.0	1.01	0.10	1.0000	OK	-
DS/POLARDAMP6-7.1.3-1	16.0	0.1	0.83	0.10	1.0000	OK	-
DS/POLARDAMP7-8.1.2-4	16.0	0.0	0.95	0.10	1.0000	OK	HEW5-1
DS/POLARDAMP7-8.1.3-4	16.0	1.2	0.82	0.10	1.0000	OK	HEW5-1
DS/POLARDAMP7-8.1.4-2	16.0	2.9	0.65	0.10	1.0000	OK	ST53S
DS/POLARDAMP7-8.1.4-4	16.0	0.6	0.81	0.10	1.0000	OK	ST53S
DS/POLARDAMP8-9.1.2-3	16.0	3.5	0.75	0.10	1.0000	OK	HEW5-1
DS/POLARDAMP8-9.1.3-1	16.0	4.7	0.66	0.10	1.0000	OK	ST53S
DS/POLARDAMP8-9.1.3-3	16.0	5.1	0.70	0.10	1.0000	OK	ST53S
DS/POLARDAMP10-11.1.2-3	16.0	3.5	0.75	0.10	1.0000	OK	HEW6
DS/POLARDAMP10-11.1.3-1	16.0	4.7	0.66	0.10	1.0000	OK	ST73
DS/POLARDAMP10-11.1.3-3	16.0	4.7	0.66	0.10	1.0000	OK	ST73
DS/POLARDAMP11-12.1.2-3	16.0	0.0	0.88	0.10	1.0000	OK	HEW6
DS/POLARDAMP11-12.1.3-1	16.0	0.0	0.68	0.10	1.0000	OK	ST73
DS/POLARDAMP11-12.1.3-3	16.0	0.0	0.74	0.10	1.0000	OK	ST73
DS/POLARDAMP13-14.1.2-3	16.0	0.0	0.85	0.10	1.0000	OK	-
DS/POLARDAMP13-14.1.3-1	0.0	0.0	0.00	0.00	0.0000	NOT MET	ST93

CASE	RANGESOL deg	HEEL deg	GZMAXR m	GZMAXS m	SFACSOL	STAT	OPEN
DS/POLARDAMP13-14.1.3-3	3.8	0.0	0.06	0.06	0.5829	NOT MET	ST93
DS/POLARDAMP14-15.1.2-3	16.0	0.0	0.83	0.10	1.0000	OK	-
DS/POLARDAMP14-15.1.3-1	0.0	0.1	0.00	0.00	0.0000	NOT MET	ST93
DS/POLARDAMP14-15.1.3-3	3.5	0.2	0.04	0.04	0.5225	NOT MET	ST93
DS/POLARDAMP16-17.1.2-3	16.0	1.1	0.83	0.10	1.0000	OK	-
DS/POLARDAMP16-17.1.3-3	16.0	0.0	0.72	0.10	1.0000	OK	ST113
DS/POLARDAMP17-18.1.2-3	16.0	0.0	0.93	0.10	1.0000	OK	-
DS/POLARDAMP17-18.1.3-3	16.0	0.0	0.85	0.10	1.0000	OK	ST113
DS/POLARDAMP18-19.1.2-4	16.0	1.2	0.89	0.10	1.0000	OK	-
DS/POLARDAMP18-19.1.3-1	16.0	1.1	0.83	0.10	1.0000	OK	-
DS/POLARDAMP18-19.1.4-4	16.0	0.1	0.73	0.10	1.0000	OK	ST113
DS/POLARDAMP19-20.1.1	16.0	1.4	0.93	0.10	1.0000	OK	-
DS/POLARDAMP19-20.1.2-3	16.0	0.0	0.91	0.10	1.0000	OK	-
DS/POLARDAMP19-20.1.2	16.0	1.3	0.87	0.10	1.0000	OK	-
DS/POLARDAMP19-20.1.3-1	16.0	0.0	0.79	0.10	1.0000	OK	HEW11
DS/POLARDAMP19-20.1.3-3	16.0	0.0	0.85	0.10	1.0000	OK	HEW11
DS/POLARDAMP20-21.1.1	16.0	1.3	0.99	0.10	1.0000	OK	-
DS/POLARDAMP20-21.1.2-3	16.0	1.3	0.89	0.10	1.0000	OK	-
DS/POLARDAMP20-21.1.2	16.0	1.2	0.95	0.10	1.0000	OK	-
DS/POLARDAMP20-21.1.3-3	16.0	0.0	0.87	0.10	1.0000	OK	-
DS/POLARDAMP20-21.1.3	16.0	1.1	0.90	0.10	1.0000	OK	-
DS/POLARDAMP20-21.1.4-1	16.0	0.1	0.63	0.10	1.0000	OK	ST133
DS/POLARDAMP20-21.1.4-3	16.0	0.1	0.73	0.10	1.0000	OK	ST133
DS/POLARDAMP21-22.1.3-4	16.0	0.0	0.77	0.10	1.0000	OK	ST133
DS/POLARDAMP23-24.1.4-4	16.0	0.0	0.88	0.10	1.0000	OK	ST153P
DS/POLARDAMP24-25.1.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/POLARDAMP24-25.1.2-3	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/POLARDAMP24-25.1.2	16.0	0.0	0.99	0.10	1.0000	OK	-
DS/POLARDAMP24-25.1.3-1	16.0	0.0	0.96	0.10	1.0000	OK	ST153P
DS/POLARDAMP24-25.1.3-3	16.0	0.0	0.95	0.10	1.0000	OK	ST153P
DS/POLARDAMP24-25.1.3	16.0	0.0	0.97	0.10	1.0000	OK	ST153P

CASE	RANGESOL deg	HEEL deg	GZMAXR m	GZMAXS m	SFACSOL	STAT	OPEN
DS/PC_BOTTOP2.2.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOP4.3.1	16.0	0.3	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOP5.3.1	16.0	0.3	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOP6.2.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOP6.3.1	16.0	0.1	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOP12.1.1	16.0	0.0	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOP12.2.1	16.0	0.4	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOP13.1.1	16.0	0.8	0.94	0.10	1.0000	OK	-
DS/PC_BOTTOP13.2.1	16.0	1.4	0.94	0.10	1.0000	OK	-
DS/PC_BOTTOP13.3.1	16.0	1.3	0.95	0.10	1.0000	OK	-
DS/PC_BOTTOP15.1.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOP15.2.1	16.0	0.5	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOP20.1.1	16.0	0.0	1.01	0.10	1.0000	OK	-
DS/PC_BOTTOP20.2.1	16.0	0.0	1.03	0.10	1.0000	OK	-
DS/PC_BOTTOP21.1.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOP23.1.1	16.0	0.0	0.98	0.10	1.0000	OK	-

CASE	RANGESOL deg	HEEL deg	GZMAXR m	GZMAXS m	SFACSOL STAT	OPEN
DS/PC_BOTTOP25.1.4-1	16.0	0.0	0.98	0.10	1.0000 OK	-
DS/PC_BOTTOP12-13.1.1	16.0	0.8	0.97	0.10	1.0000 OK	-
DS/PC_BOTTOP12-13.2.1	16.0	1.7	0.96	0.10	1.0000 OK	-
DS/PC_BOTTOP12-13.3.1	16.0	1.6	0.98	0.10	1.0000 OK	-
DS/PC_BOTTOP13-14.1.1	16.0	0.8	0.96	0.10	1.0000 OK	-
DS/PC_BOTTOP13-14.2.1	16.0	1.8	0.95	0.10	1.0000 OK	-
DS/PC_BOTTOP13-14.3.1	16.0	1.8	0.97	0.10	1.0000 OK	-
DS/PC_BOTTOP15-16.1.1	16.0	0.0	1.02	0.10	1.0000 OK	-
DS/PC_BOTTOP16-17.1.1	16.0	0.0	1.01	0.10	1.0000 OK	-
DS/PC_BOTTOP17-18.1.1	16.0	1.3	0.97	0.10	1.0000 OK	-
DS/PC_BOTTOP17-18.3.1	16.0	1.3	1.00	0.10	1.0000 OK	-
DS/PC_BOTTOP18-19.1.1	16.0	1.4	0.93	0.10	1.0000 OK	-
DS/PC_BOTTOP18-19.2.1	16.0	1.4	0.96	0.10	1.0000 OK	-
DS/PC_BOTTOP19-20.1.1	16.0	1.3	0.97	0.10	1.0000 OK	-
DS/PC_BOTTOP19-20.2.1	16.0	1.3	0.99	0.10	1.0000 OK	-
DS/PC_BOTTOP19-20.3.1	16.0	1.3	1.02	0.10	1.0000 OK	-
DS/PC_BOTTOP20-21.1.1	16.0	0.0	1.02	0.10	1.0000 OK	-
DS/PC_BOTTOP22-23.1.1	16.0	0.0	0.99	0.10	1.0000 OK	-
DS/PC_BOTTOP24-25.1.1	16.0	0.0	0.99	0.10	1.0000 OK	-

Starboard side results, including side and bottom area damages.

CASE	RANGESOL deg	HEEL deg	GZMAXR m	GZMAXS m	SFACSOL STAT	OPEN
DS/POLARDAMS2.1.2-1	16.0	0.0	0.86	0.10	1.0000 OK	ST23-1
DS/POLARDAMS2.2.1	16.0	0.0	0.98	0.10	1.0000 OK	-
DS/POLARDAMS2.2.2	16.0	0.0	0.87	0.10	1.0000 OK	ST23-1
DS/POLARDAMS4.1.1	16.0	-0.3	0.98	0.10	1.0000 OK	-
DS/POLARDAMS4.1.3-2	16.0	-0.3	0.89	0.10	1.0000 OK	-
DS/POLARDAMS5.1.1	16.0	-0.3	0.98	0.10	1.0000 OK	-
DS/POLARDAMS6.1.2-1	16.0	-1.3	0.84	0.10	1.0000 OK	-
DS/POLARDAMS6.1.3-2	16.0	-0.2	0.92	0.10	1.0000 OK	-
DS/POLARDAMS8.1.2-1	16.0	0.0	0.94	0.10	1.0000 OK	HEW5-1
DS/POLARDAMS8.1.3-1	16.0	0.1	0.86	0.10	1.0000 OK	ST53S
DS/POLARDAMS8.1.3-2	16.0	0.0	0.89	0.10	1.0000 OK	ST53S
DS/POLARDAMS9.1.2-1	16.0	-3.9	0.79	0.10	1.0000 OK	-
DS/POLARDAMS11.1.2-1	16.0	0.0	0.94	0.10	1.0000 OK	HEW6
DS/POLARDAMS11.1.3-1	16.0	-0.5	0.85	0.10	1.0000 OK	ST73
DS/POLARDAMS11.1.3-2	16.0	-0.3	0.89	0.10	1.0000 OK	ST73
DS/POLARDAMS12.1.2-1	16.0	0.0	0.90	0.10	1.0000 OK	-
DS/POLARDAMS12.1.3-1	16.0	0.0	0.79	0.10	1.0000 OK	ST83
DS/POLARDAMS12.1.3-2	16.0	0.0	0.86	0.10	1.0000 OK	ST83
DS/POLARDAMS14.1.2-1	16.0	0.0	0.90	0.10	1.0000 OK	-
DS/POLARDAMS14.1.3-1	16.0	-0.1	0.77	0.10	1.0000 OK	ST93
DS/POLARDAMS14.1.3-2	16.0	-0.1	0.83	0.10	1.0000 OK	ST93
DS/POLARDAMS16.1.2-1	16.0	0.0	0.87	0.10	1.0000 OK	-
DS/POLARDAMS16.1.3-1	16.0	0.0	0.74	0.10	1.0000 OK	ST103
DS/POLARDAMS16.1.3-2	16.0	0.0	0.83	0.10	1.0000 OK	ST103
DS/POLARDAMS21.1.1	16.0	0.0	1.03	0.10	1.0000 OK	-
DS/POLARDAMS21.1.2-1	16.0	0.1	0.92	0.10	1.0000 OK	-
DS/POLARDAMS21.1.3-1	16.0	0.2	0.80	0.10	1.0000 OK	ST133
DS/POLARDAMS21.1.3-2	16.0	0.0	0.85	0.10	1.0000 OK	ST133
DS/POLARDAMS22.1.3-2	16.0	0.0	0.90	0.10	1.0000 OK	-
DS/POLARDAMS3-4.1.1	16.0	-0.3	0.99	0.10	1.0000 OK	-
DS/POLARDAMS3-4.1.4-4	16.0	-0.9	0.78	0.10	1.0000 OK	ST23-1

CASE	RANGESOL deg	HEEL deg	GZMAXR m	GZMAXS m	SFACSOL	STAT	OPEN
DS/POLARDAMS4-5.1.1	16.0	-0.6	0.98	0.10	1.0000	OK	-
DS/POLARDAMS5-6.1.1	16.0	-0.4	1.01	0.10	1.0000	OK	-
DS/POLARDAMS5-6.1.3-3	16.0	-0.6	0.84	0.10	1.0000	OK	-
DS/POLARDAMS6-7.1.1	16.0	-0.1	0.99	0.10	1.0000	OK	-
DS/POLARDAMS6-7.1.3-1	16.0	-1.8	0.79	0.10	1.0000	OK	-
DS/POLARDAMS7-8.1.2-4	16.0	-0.1	0.96	0.10	1.0000	OK	HEW5-3
DS/POLARDAMS7-8.1.3-4	16.0	-1.2	0.82	0.10	1.0000	OK	HEW5-3
DS/POLARDAMS7-8.1.4-2	9.6	-2.2	0.44	0.10	0.8809	NOT MET	ST53S
DS/POLARDAMS7-8.1.4-4	16.0	-0.3	0.83	0.10	1.0000	OK	ST53S
DS/POLARDAMS8-9.1.2-3	16.0	-3.5	0.75	0.10	1.0000	OK	HEW5-3
DS/POLARDAMS8-9.1.3-1	10.0	-4.6	0.48	0.10	0.8885	NOT MET	ST53S
DS/POLARDAMS8-9.1.3-3	14.5	-5.0	0.67	0.10	0.9761	NOT MET	ST53S
DS/POLARDAMS10-11.1.2-3	16.0	-3.5	0.75	0.10	1.0000	OK	HEW6
DS/POLARDAMS10-11.1.3-1	13.2	-4.6	0.62	0.10	0.9524	NOT MET	ST73
DS/POLARDAMS10-11.1.3-3	16.0	-4.9	0.71	0.10	1.0000	OK	ST73
DS/POLARDAMS11-12.1.2-3	16.0	0.0	0.88	0.10	1.0000	OK	HEW6
DS/POLARDAMS11-12.1.3-1	15.4	-0.8	0.64	0.10	0.9902	NOT MET	ST73
DS/POLARDAMS11-12.1.3-3	16.0	-0.5	0.79	0.10	1.0000	OK	ST73
DS/POLARDAMS13-14.1.2-3	16.0	0.0	0.85	0.10	1.0000	OK	-
DS/POLARDAMS13-14.1.3-1	0.0	-0.1	0.00	0.00	0.0000	NOT MET	ST93
DS/POLARDAMS13-14.1.3-3	16.0	-0.1	0.72	0.10	1.0000	OK	ST93
DS/POLARDAMS14-15.1.2-3	16.0	0.0	0.83	0.10	1.0000	OK	-
DS/POLARDAMS14-15.1.3-1	0.0	-0.1	0.00	0.00	0.0000	NOT MET	ST93
DS/POLARDAMS14-15.1.3-3	16.0	-0.2	0.70	0.10	1.0000	OK	ST93
DS/POLARDAMS16-17.1.2-3	16.0	-2.2	0.78	0.10	1.0000	OK	-
DS/POLARDAMS16-17.1.3-3	16.0	0.0	0.72	0.10	1.0000	OK	ST113
DS/POLARDAMS17-18.1.2-3	16.0	-2.4	0.87	0.10	1.0000	OK	-
DS/POLARDAMS17-18.1.3-3	16.0	0.0	0.85	0.10	1.0000	OK	ST113
DS/POLARDAMS18-19.1.2-4	16.0	-3.5	0.86	0.10	1.0000	OK	-
DS/POLARDAMS18-19.1.3-1	16.0	-3.3	0.79	0.10	1.0000	OK	-
DS/POLARDAMS18-19.1.4-4	16.0	0.0	0.74	0.10	1.0000	OK	ST113
DS/POLARDAMS19-20.1.1	16.0	-1.4	0.96	0.10	1.0000	OK	-
DS/POLARDAMS19-20.1.2-3	16.0	0.0	0.90	0.10	1.0000	OK	-
DS/POLARDAMS19-20.1.2	16.0	-1.3	0.89	0.10	1.0000	OK	-
DS/POLARDAMS19-20.1.3-1	16.0	0.0	0.79	0.10	1.0000	OK	HEW11
DS/POLARDAMS19-20.1.3-3	16.0	0.0	0.85	0.10	1.0000	OK	HEW11
DS/POLARDAMS20-21.1.1	16.0	-1.3	1.02	0.10	1.0000	OK	-
DS/POLARDAMS20-21.1.2-3	16.0	-1.2	0.92	0.10	1.0000	OK	-
DS/POLARDAMS20-21.1.2	16.0	-1.1	0.98	0.10	1.0000	OK	-
DS/POLARDAMS20-21.1.3-3	16.0	0.1	0.86	0.10	1.0000	OK	-
DS/POLARDAMS20-21.1.3	16.0	-1.1	0.92	0.10	1.0000	OK	-
DS/POLARDAMS20-21.1.4-1	16.0	0.5	0.62	0.10	1.0000	OK	ST133
DS/POLARDAMS20-21.1.4-3	16.0	0.1	0.73	0.10	1.0000	OK	ST133
DS/POLARDAMS21-22.1.3-4	16.0	0.0	0.77	0.10	1.0000	OK	ST133
DS/POLARDAMS23-24.1.4-4	16.0	0.0	0.88	0.10	1.0000	OK	ST153P
DS/POLARDAMS24-25.1.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/POLARDAMS24-25.1.2-3	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/POLARDAMS24-25.1.2	16.0	0.0	0.99	0.10	1.0000	OK	-
DS/POLARDAMS24-25.1.3-1	16.0	0.0	0.96	0.10	1.0000	OK	ST153P
DS/POLARDAMS24-25.1.3-3	16.0	0.0	0.95	0.10	1.0000	OK	ST153P
DS/POLARDAMS24-25.1.3	16.0	0.0	0.97	0.10	1.0000	OK	ST153P

CASE	RANGESOL deg	HEEL deg	GZMAXR m	GZMAXS m	SFACSOL	STAT	OPEN
DS/PC_BOTTOS2.2.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS4.3.1	16.0	-0.3	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS5.3.1	16.0	-0.3	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS6.2.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS6.3.1	16.0	-0.1	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS6.4.1	16.0	-0.1	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOS12.1.1	16.0	0.0	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOS12.2.1	16.0	-0.4	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOS12.3.1	16.0	-0.4	1.00	0.10	1.0000	OK	-
DS/PC_BOTTOS13.1.1	16.0	-0.8	0.94	0.10	1.0000	OK	-
DS/PC_BOTTOS13.2.1	16.0	-1.4	0.94	0.10	1.0000	OK	-
DS/PC_BOTTOS15.1.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS15.2.1	16.0	-0.5	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS15.3.1	16.0	-0.5	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOS20.1.1	16.0	0.0	1.01	0.10	1.0000	OK	-
DS/PC_BOTTOS20.2.1	16.0	0.0	1.03	0.10	1.0000	OK	-
DS/PC_BOTTOS21.1.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS23.1.1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS25.1.4-1	16.0	0.0	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS3-4.1.1	16.0	-0.3	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOS4-5.1.1	16.0	-0.6	0.98	0.10	1.0000	OK	-
DS/PC_BOTTOS5-6.1.1	16.0	-0.3	1.00	0.10	1.0000	OK	-
DS/PC_BOTTOS5-6.5.1	16.0	-0.4	1.00	0.10	1.0000	OK	-
DS/PC_BOTTOS5-6.6.1	16.0	-0.4	1.01	0.10	1.0000	OK	-
DS/PC_BOTTOS12-13.1.1	16.0	-0.8	0.97	0.10	1.0000	OK	-
DS/PC_BOTTOS12-13.2.1	16.0	-1.7	0.96	0.10	1.0000	OK	-
DS/PC_BOTTOS13-14.1.1	16.0	-0.8	0.96	0.10	1.0000	OK	-
DS/PC_BOTTOS13-14.2.1	16.0	-1.8	0.95	0.10	1.0000	OK	-
DS/PC_BOTTOS15-16.1.1	16.0	0.0	1.02	0.10	1.0000	OK	-
DS/PC_BOTTOS15-16.3.1	16.0	-0.5	1.02	0.10	1.0000	OK	-
DS/PC_BOTTOS15-16.4.1	16.0	-0.5	1.03	0.10	1.0000	OK	-
DS/PC_BOTTOS16-17.1.1	16.0	0.0	1.01	0.10	1.0000	OK	-
DS/PC_BOTTOS17-18.1.1	16.0	-1.3	0.97	0.10	1.0000	OK	-
DS/PC_BOTTOS17-18.3.1	16.0	-1.3	1.00	0.10	1.0000	OK	-
DS/PC_BOTTOS18-19.1.1	16.0	-1.4	0.93	0.10	1.0000	OK	-
DS/PC_BOTTOS18-19.2.1	16.0	-1.4	0.96	0.10	1.0000	OK	-
DS/PC_BOTTOS19-20.1.1	16.0	-1.3	0.97	0.10	1.0000	OK	-
DS/PC_BOTTOS19-20.2.1	16.0	-1.3	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOS19-20.3.1	16.0	-1.3	1.02	0.10	1.0000	OK	-
DS/PC_BOTTOS20-21.1.1	16.0	0.0	1.02	0.10	1.0000	OK	-
DS/PC_BOTTOS22-23.1.1	16.0	0.0	0.99	0.10	1.0000	OK	-
DS/PC_BOTTOS24-25.1.1	16.0	0.0	0.99	0.10	1.0000	OK	-

Appendix 3. Interview at Aker Arctic Ltd.

Aker Arctic is one of the world leading ship design office for ice going ships. The ship designers interviewed at Aker Arctic on 26.01.2017 were naval architect, senior project manager Mr. Mika Hovilainen and senior project manager Mr. Maximillian Vocke.

The Scope behind the interview of the industry is to highlight how the ships intended for polar water operations were designed before the Polar Code, and how the new Polar Code has changed the situation. The interviews may also reveal demands or useful details that need to be considered in stability –tool development.

The review was carried with 10 questions, and also by open questions and discussion. The list of questions and refracted answers are shown below this text.

Questions for Aker Arctic

1. *In general, what new aspects the Polar Code brings to arctic ship design?*
   What is old and what is new?
2. *Is there something against common sense or odd?*
3. *What are especially good safety increasing regulations, not considered before?*
4. *How you have considered icing in your past ship designs? How it is implemented to stability study/criteria?*
5. *How is the damage stability calculated before? Especially how damage generation is carried out/was there some deterministic damage scenario?*
6. *Are you aware where the extent of the deterministic damage comes from/its reasons?*
   a. *legnth, height?*
   b. *penetration (76cm?)*
7. *How you feel this is in line with damage statistics from polar area operations?*
8. *Have you ideas/notes for the stability tool in question in the thesis?*
9. *What kind of NAPA-model would be interesting and good for the analysis?*
10. *Questions for the thesis and discussion.*

The answers for questions above questions were following. The answers do not represent the answers from the interview word-by-word, but are summarized by the context of the interview. The recording of the interview is available from the author.

Answers:

1. *In general, what new aspects the Polar Code brings to arctic ship design?*
   What is old and what is new?

A: Before Polar Code there has been similar requirements called IMO Resolution A.1024(26), Guidelines for Ships Operating in Polar Waters. Similar damage stability requirements exists already in A.1026. Polar Code brings more awareness and requirements related to special circumstances that can happen these sea areas. In these areas ships are far away from help. At the moment there is no clear requirement how long time in the polar area the ship has to be designed, before rescue arrives. Designs can vary from 5 to 60 days to provide safety for the crew and passengers to wait for the help to arrive. The stability related chapter in Polar Code is the only clearly defined requirements with clear limits and definitions.

2. *Is there something against common sense or odd?*

A: The amount of icing that can accumulate on superstructure is rather small. In the past projects Aker Arctic has used higher values for ice accumulating in the past ship designs. Also the general feeling towards Polar Code was that it is too indefinite because there is too much interpretation for the requirements.

3. *What are especially good safety increasing regulations, not considered before?*

Most part of the Polar Code requirements are such which have been taken into account in ship design already before Polar Code. One particular improvement in Polar Code to previous situation is how the ship is prepared for evacuation in remote and harsh conditions. Special equipment and procedures for such event improves possibility to survive. Other improvement from previous A.1024 requirement is that Polar Code does not anymore require the study of peaching and ship strength in that situation. For long vessels such as tankers and cargo ships that sort of situation is impossible since no ice can with stand such pressure caused by the ship bow rising on the ice.

4. *How you have considered icing in your past ship designs? How it is implemented to stability study/criteria?*

A: For icebreakers and cargo ships the icing is not considered as a problem because of the relatively high GM that allows some added mass to be placed on high coordinates. For cruise ships, the effect of icing can potentially be more significant. Cruise ships GM is smaller to ensure passenger comfort with slow accelerations. So accumulated ice on high decks that may have plenty of possible deck area for ice to accumulate can have effect on vessels intact stability.

5. *How is the intact stability concerning icing calculated before?*

A: Side projection and exposed deck area has usually been taken from CAD drawing as well as the CoG/geometrical center points for these areas. Then with these information it is quite straight forward to calculate total CoG of the accumulated ice. This approach is at least efficient for cargo ships, which has rather simple superstructure. More automated and possibly NAPA model utilizing method could be useful with cruise ships that have more complicated superstructure and many decks.

In the past classification societies have required larger ice loads to be used. For example on decks 300kg/m^2, not 30kg/m^2 as in Polar Code and IS code (IMO IS Code). Also in ship design and stability calculations, it has been common practice to round up the deck areas and thus also the amount accumulated ice, to have conservative estimation for the extra mass. Also the Polar Code instructs to use certain percentages to increase the amount of accumulated ice, as the IS Code in the past.

6. *How the authorities validate and interprets the Polar Code requirements from ship designs?*

A: Not that much. Design features and needed information shall be written to the Polar Water Operational Manual (aka PWOM) and the class society or statutory authority stamps the manual to confirm that Polar Code's design aspects and requirements has been taken account. At the moment, the organization who gives insurance for the ship and operator may be the most interested in about how the vessel fulfills the Polar Code requirements. Especially if accident happens and it is time, find the reason for the accident. At the moment it seems like no-one is clearly appointed to be the supervisor of the interpretation of Polar Code. This allows ship designers or owners to interpret the Polar Code as lightly as possible and thus find ways to save money with the cost of compromising the safety.

7. *How is the damage stability calculated before? Especially how damage generation is carried out/was there some deterministic damage scenario?*

A: Aker Arctic typically designs all ice going ships with double sides that are usually around 1m wide. Damages are generated manually, which is already quite laborious with icebreakers and cargo ships. In case of arctic cruise ship, automatized generation is surely very useful. The damage extent as defined in the Polar Code is sensible. The penetration depth of 760mm is conservative, for damages they have heard of to be caused by ice compression or ramming. Idea of ice caused damages is already familiar and used by (some?) class-rules and especially Russian register that is quite similar to Polar Code. Supply vessel rules has some statistic for determining the 760mm damage penetration. Aker Arctic/they were not familiar with an accident where double side would have been punctured. In addition, 760mm double side is very tight in construction point of view.

8. *Are you aware where the extent of the deterministic damage comes from/its reasons?*
    a. *Length, height?*

    A: Sensible dimensions.

    b. *Penetration (76cm?)*

    A: Maybe used already in some supply vessel code. Mentioned in year 2002 guidelines for arctic/polar ship design.

9. How you feel this is in line with damage statistics from polar area operations?

A: Typical damages in ice does not influence flooding. Plate is typically bended without more severe failure. If more severe failure happens, most propbably it is within current damage extentions.

10. Have you ideas/notes for the stability tool in question in the thesis?

A: In intact stability calculation the maximum loading condition is not necessarily the most dangerous situation. So it might be good to put the effect of icing to the limit curve, not to loading conditions.

11. What kind of NAPA-model would be interesting and good for the analysis?

A: Aker's ships not that interesting since all have double side. Possibly some cruise ship would be interesting and make it have a damage at the intersection of four watertight zones. This would be interesting and quite possible scenario

12. General discussion and thoughts

A: Polar Code could be developed to have more accurately defined requirements, now there is too much space for interpretation that may lead to decrease in safety. Every ship designer should be able to come up to similar outcome with same rules. The responsibility of supervision of how Polar Code is fulfilled in ship designs should be assigned clearly to some authority.

Appendix 4. List of intact stability criteria and results for used example ships

FLOODSTAND-B

Light loading condition with ice:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve.	0.055	0.306	mrad	OK
V.AREA40	Area under GZ curve.	0.090	0.445	mrad	OK
V.AREA3040	Area under GZ curve .	0.030	0.139	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	0.957	m	OK
V.MAXGZ25	Max. GZ at an angle .	25.000	28.512	deg	OK
V.GM0.15	GM > 0.15 m	0.150	2.390	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	1.771	deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	2.558	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.155		OK
LR.IMOWINDHEE.HEEL	< 16 deg	16.000	5.034	deg	OK
LR.IMOWINDHEE.HEEL	< 80% of FRB im.	26.392	5.034	deg	OK

Heavy loading condition with ice:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve .	0.055	0.333	mrad	OK
V.AREA40	Area under GZ curve .	0.090	0.506	mrad	OK
V.AREA3040	Area under GZ curve .	0.030	0.173	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	1.135	m	OK
V.MAXGZ25	Max. GZ at an angle .	25.000	30.477	deg	OK
V.GM0.15	GM > 0.15 m	0.150	2.488	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	1.553	deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	2.357	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.839		OK
LR.IMOWINDHEE.HEEL	< 16 deg	16.000	3.530	deg	OK
LR.IMOWINDHEE.HEEL	< 80% of FRB im.	24.685	3.530	deg	OK

Light loading condition with 10X larger icing:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve.	0.055	0.111	mrad	OK
V.AREA40	Area under GZ curve.	0.090	0.138	mrad	OK
V.AREA3040	Area under GZ curve	0.030	0.026	mrad	NOT MET
V.GZ0.2	Min. GZ > 0.2	0.200	0.364	m	OK
V.MAXGZ25	Max. GZ at an angle.	25.000	27.587	deg	OK
V.GM0.15	GM > 0.15 m	0.150	0.765	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	4.700	deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	8.199	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	0.525		NOT MET
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	10.203	deg	OK
LR.IMOWINDHEEL2	HEEL < 80% of FRB im.	22.971	10.203	deg	OK

Unsymmetrical icing on P-side of the ship, as per PC:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve .	0.055	0.297	mrad	OK
V.AREA40	Area under GZ curve .	0.090	0.439	mrad	OK
V.AREA3040	Area under GZ curve .	0.030	0.142	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	0.965	m	OK
V.MAXGZ25	Max. GZ at an angle .	25.000	28.758	deg	OK
V.GM0.15	GM > 0.15 m	0.150	2.506	m	OK
LR.MAXHEELPASS	Max. heel due to cro.	10.000	2.769	deg	OK
LR.MAXHEELTURN	Max. heel due to tur.	10.000	3.491	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.267		OK
LR.IMOWINDHEE.	HEEL < 16 deg	16.000	5.041	deg	OK
LR.IMOWINDHEE.	HEEL < 80% of FRB im.	26.502	5.041	deg	OK

Bulk Carrier

Light loading condition with ice:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve .	0.055	0.509	mrad	OK
V.AREA40	Area under GZ curve .	0.090	1.036	mrad	OK
V.AREA3040	Area under GZ curve .	0.030	0.527	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	3.506	m	OK
V.MAXGZ25	Max. GZ at an angle .	25.000	46.320	deg	OK
V.GM0.15	GM > 0.15 m	0.150	3.723	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	3.948	deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	6.502	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	8.446		OK
LR.IMOWINDHEE.HEEL	< 16 deg	16.000	4.196	deg	OK
LR.IMOWINDHEE.HEEL	< 80% of FRB im.	22.061	4.196	deg	OK

Heavy loading condition with ice:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve .	0.055	0.429	mrad	OK
V.AREA40	Area under GZ curve .	0.090	0.749	mrad	OK
V.AREA3040	Area under GZ curve .	0.030	0.321	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	1.941	m	OK
V.MAXGZ25	Max. GZ at an angle .	25.000	43.312	deg	OK
V.GM0.15	GM > 0.15 m	0.150	3.669	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	3.005	deg	OK
LR.MAXHEELTURN	Max. heel due to turning.	10.000	6.033	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	4.430		OK
LR.IMOWINDHEE.HEEL	< 16 deg	16.000	3.059	deg	OK
LR.IMOWINDHEE.HEEL	< 80% of FRB im.	12.480	3.059	deg	OK

Light loading condition with 10X higher icing allowance:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve.	0.055	0.465	mrad	OK
V.AREA40	Area under GZ curve.	0.090	0.952	mrad	OK
V.AREA3040	Area under GZ curve.	0.030	0.487	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	3.213	m	OK
V.MAXGZ25	Max. GZ at an angle.	25.000	45.690	deg	OK
V.GM0.15	GM > 0.15 m	0.150	3.396	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	4.208	deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	7.106	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	8.678		OK
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	4.360	deg	OK
LR.IMOWINDHEEL2	HEEL < 80% of FRB im	21.557	4.360	deg	OK

Unsymmetrical icing on P-side of the ship, as per PC:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve	0.055	0.514	mrad	OK
V.AREA40	Area under GZ curve	0.090	1.049	mrad	OK
V.AREA3040	Area under GZ curve.	0.030	0.535	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	3.570	m	OK
V.MAXGZ25	Max. GZ at an angle.	25.000	46.507	deg	OK
V.GM0.15	GM > 0.15 m	0.150	3.811	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	4.131	deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	6.572	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	8.435		OK
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	4.277	deg	OK
LR.IMOWINDHEEL2	HEEL < 80% of FRB im.	22.184	4.277	deg	OK

Naval Frigate

Light loading condition with ice:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve .	0.055	0.033	mrad	NOT MET
V.AREA40	Area under GZ curve .	0.090	0.073	mrad	NOT MET
V.AREA3040	Area under GZ curve .	0.030	0.040	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	0.301	m	OK
V.MAXGZ25	Max. GZ at an angle .	25.000	41.616	deg	OK
V.GM0.15	GM > 0.15 m	0.150	0.221	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	11.215	deg	NOT MET
LR.MAXHEELTURN	Max. heel due to turning	10.000	0.000	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.581		OK
LR.IMOWINDHEE.HEEL	< 16 deg	16.000	23.902	deg	NOT MET
LR.IMOWINDHEE.HEEL	< 80% of FRB im.	28.656	23.902	deg	OK

Heavy loading condition with ice:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve .	0.055	0.131	mrad	OK
V.AREA40	Area under GZ curve .	0.090	0.247	mrad	OK
V.AREA3040	Area under GZ curve .	0.030	0.116	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	0.796	m	OK
V.MAXGZ25	Max. GZ at an angle .	25.000	43.447	deg	OK
V.GM0.15	GM > 0.15 m	0.150	0.900	m	OK
LR.MAXHEELPASS	Max. heel due to crowding	10.000	2.394	deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	0.000	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	5.714		OK
LR.IMOWINDHEE.HEEL	< 16 deg	16.000	5.127	deg	OK
LR.IMOWINDHEE.HEEL	< 80% of FRB im.	25.834	5.127	deg	OK

Light loading condition with 10X higher icing allowance:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve.	0.055	0.000	mrad	NOT MET
V.AREA40	Area under GZ curve.	0.090	0.001	mrad	NOT MET
V.AREA3040	Area under GZ curve.	0.030	0.001	mrad	NOT MET
V.GZ0.2	Min. GZ > 0.2	0.200	0.013	m	NOT MET
V.MAXGZ25	Max. GZ at an angle	25.000	38.323	deg	OK
V.GM0.15	GM > 0.15 m	0.150	-0.235	m	NOT MET
LR.MAXHEELPASS	Max. heel due to crowding.	10.000	-	deg	NOT MET
LR.MAXHEELTURN	Max. heel due to turning	10.000	34.638	deg	NOT MET
LR.IMOWEATHER	IMO weather criterion	1.000	0.000		NOT MET
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	-	deg	NOT MET
LR.IMOWINDHEEL2	HEEL < 80% of FRB im	25.987	-	deg	NOT MET

Unsymmetrical icing on P-side of the ship, as per PC:

RCR	TEXT	REQ	ATTV	UNIT	STAT
V.AREA30	Area under GZ curve.	0.055	0.020	mrad	NOT MET
V.AREA40	Area under GZ curve.	0.090	0.057	mrad	NOT MET
V.AREA3040	Area under GZ curve.	0.030	0.037	mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	0.290	m	OK
V.MAXGZ25	Max. GZ at an angle.	25.000	41.990	deg	OK
V.GM0.15	GM > 0.15 m	0.150	0.253	m	OK
LR.MAXHEELPASS	Max. heel due to crowding.	10.000	9.312	deg	OK
LR.MAXHEELTURN	Max. heel due to turning	0.000	9.312	deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.252		OK
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	27.334	deg	NOT MET
LR.IMOWINDHEEL2	HEEL < 80% of FRB im.	28.484	27.334	deg	OK

Appendix 5. Example output of results, produced by the developed ice accretion tool.

Intact stability results

NAPA/D/LD/170510		DATE 2017-06-02
FLOODSTAND-B/A		TIME 10:41
FLOODSTAND		USER TIMO
		1

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Areas and CoG -locations of superstructure decks from lowest to highest.

Area at z-coordinate level 16 m is: 2333.15 m2 and CoG is (86.6323, 0.011074, 16) Area at z-coordinate level 19.8 m is: 307.816 m2 and CoG is (230.547, 0.530499, 19.8) Area at z-coordinate level 20.8 m is: 16.2606 m2 and CoG is (210.242, 0, 20.8) Area at z-coordinate level 39.8 m is: 6249.01 m2 and CoG is (97.4916, 0, 39.8)

Deck's CoGs (xyz) are 99.4513 0.0212361 32.8392 [m] and ice mass on decks is 267187 kg.

Area of the lateral projection above waterline is 13966.8 m2 for lightweight and 13741.2 m2 for polardeep, this number includes the areas for both sides of the ship.

For lighter LC (lightweight), lateral projections CoG (xyz) is 107.242 0 22.7204 [m] and the ice mass for lateral areas is 110512 kg including both sides of the ship. The lateral ice mass consists of 104751 kg from lateral projection, and 108727 kg that takes account discontinuous surfaces (as per Polar Code).

For heavier LC (polardeep), lateral projections CoG (xyz) is 107.243 0 22.976 [m] and the ice mass for lateral areas is 108727 kg including both sides of the ship. The lateral ice mass consists of 103059 kg from lateral projection, and 5668.23 kg that takes account discontinuous surfaces (as per Polar Code).

FINAL RESULT, ADDED TO SELECTED LOADING CONDITIONS (lightweight and polardeep): Combined center of gravity for ice masses is: FOR LIGHT LC lightweight : (X=101.731 , Y=0.0150225 , Z=29.8785) and the total ice mass is 377.699 ton. FOR HEAVY LC polardeep : (X=101.705 , Y=0.0150939 , Z=29.9865) and the total ice mass is 375.914 ton.

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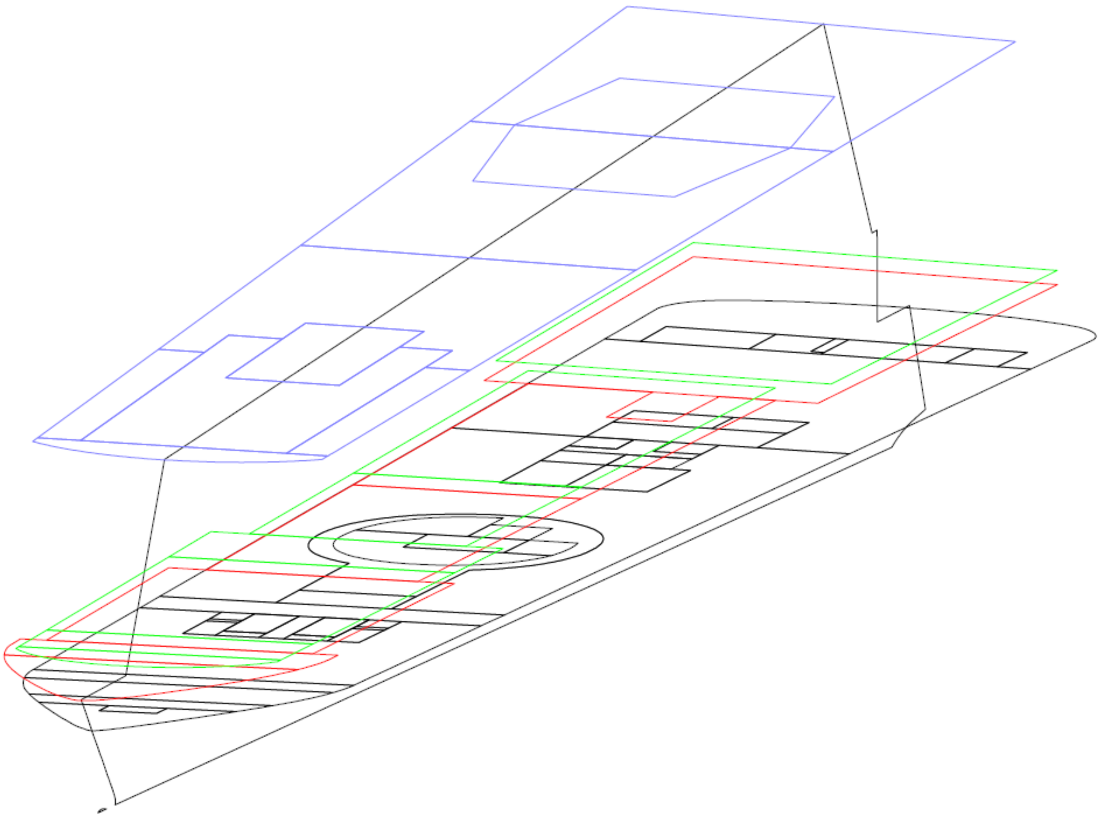


Loading condition: LIGHTWEIGHT

RCR	TEXT	REQ	ATTV UNIT	STAT
V.AREA30	Area under GZ curve up to 30 deg	0.055	0.335 mrad	OK
V.AREA40	Area under GZ curve up to 40 deg.	0.090	0.493 mrad	OK
V.AREA3040	Area under GZ curve between 30 and 40 deg	0.030	0.158 mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	1.054 m	OK
V.MAXGZ25	Max. GZ at an angle > 25 deg.	25.000	28.863 deg	OK
V.GM0.15	GM > 0.15 m	0.150	2.624 m	OK
LR.MAXHEELPASS	Max. heel due to crowding of pass.	10.000	1.632 deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	2.302 deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.416	OK
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	3.832 deg	OK
LR.IMOWINDHEEL2	HEEL < 80% of FRB immersion	26.613	3.832 deg	OK

Loading condition: LIGHT_ICE

RCR	TEXT	REQ	ATTV UNIT	STAT
V.AREA30	Area under GZ curve up to 30 deg	0.055	0.333 mrad	OK
V.AREA40	Area under GZ curve up to 40 deg.	0.090	0.506 mrad	OK
V.AREA3040	Area under GZ curve between 30 and 40 deg	0.030	0.173 mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	1.135 m	OK
V.MAXGZ25	Max. GZ at an angle > 25 deg.	25.000	30.478 deg	OK
V.GM0.15	GM > 0.15 m	0.150	2.489 m	OK
LR.MAXHEELPASS	Max. heel due to crowding of pass.	10.000	1.553 deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	2.356 deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.822	OK
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	3.587 deg	OK
LR.IMOWINDHEEL2	HEEL < 80% of FRB immersion	24.684	3.587 deg	OK

Loading condition: POLARDEEP

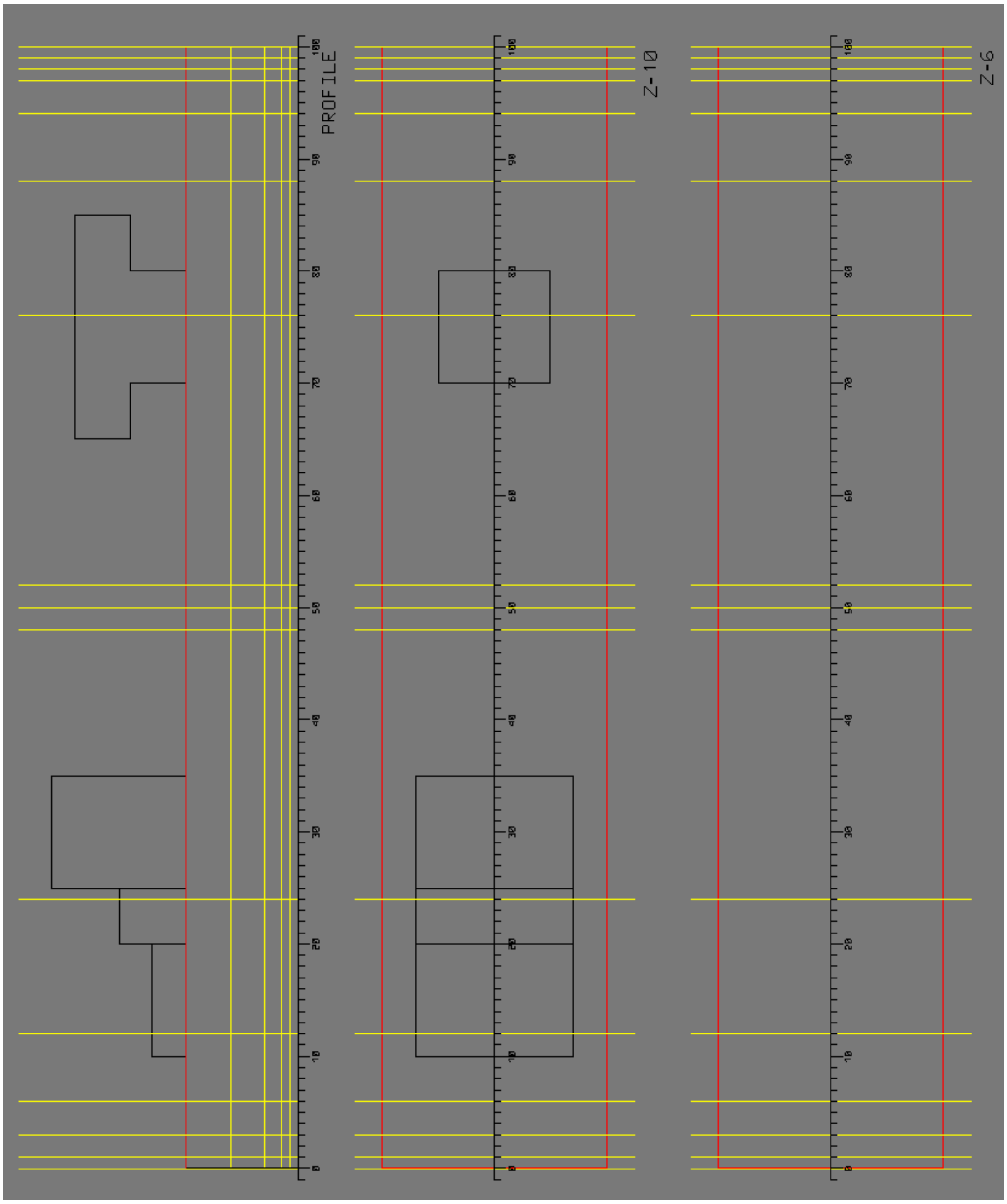
RCR	TEXT	REQ	ATTV UNIT	STAT
V.AREA30	Area under GZ curve up to 30 deg	0.055	0.360 mrad	OK
V.AREA40	Area under GZ curve up to 40 deg.	0.090	0.552 mrad	OK
V.AREA3040	Area under GZ curve between 30 and 40 deg	0.030	0.192 mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	1.228 m	OK
V.MAXGZ25	Max. GZ at an angle > 25 deg.	25.000	30.638 deg	OK
V.GM0.15	GM > 0.15 m	0.150	2.702 m	OK
LR.MAXHEELPASS	Max. heel due to crowding of pass.	10.000	1.445 deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	2.147 deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.651	OK
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	4.074 deg	OK
LR.IMOWINDHEEL2	HEEL < 80% of FRB immersion	24.883	4.074 deg	OK

Loading condition: HEAVY_ICE

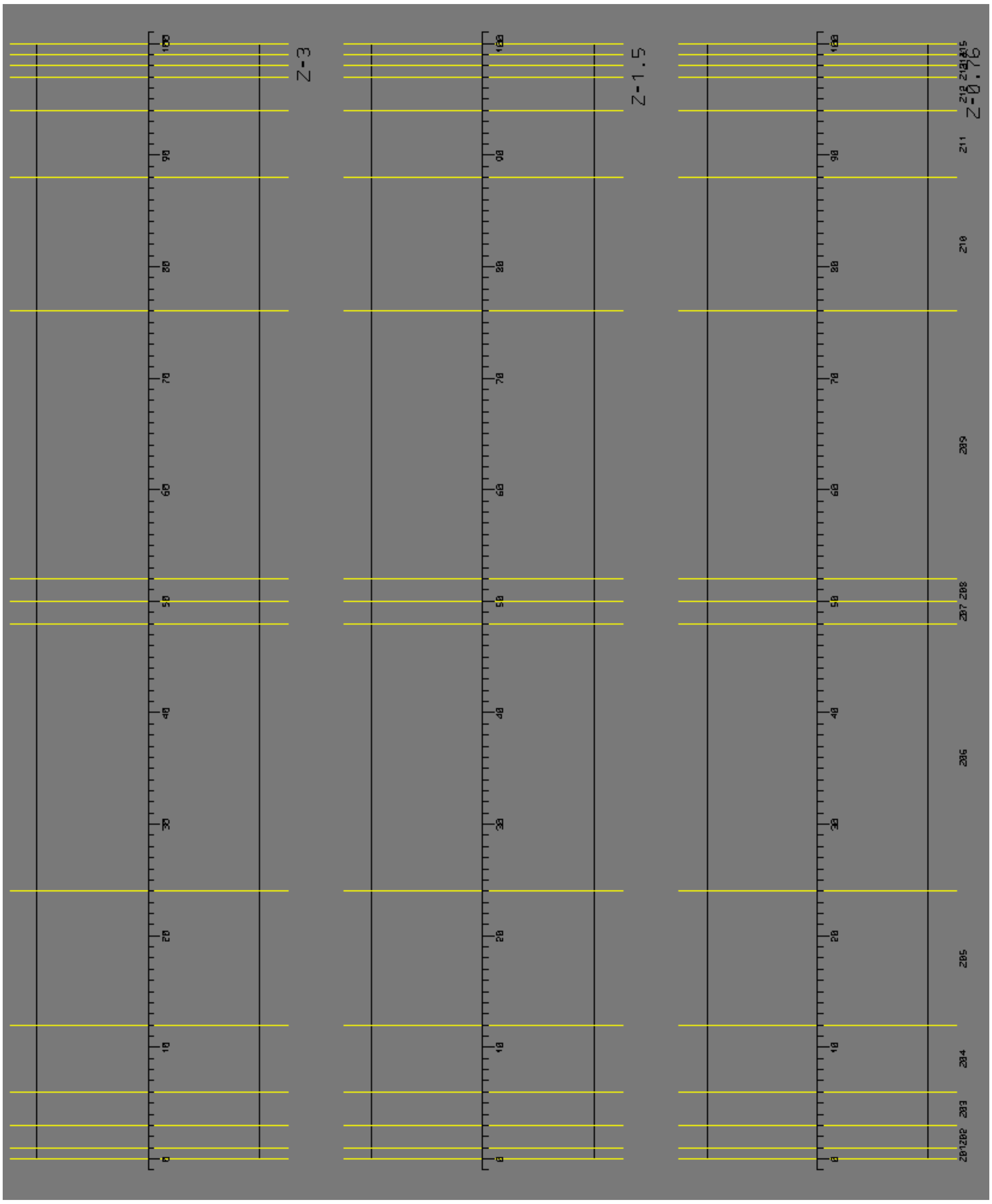
RCR	TEXT	REQ	ATTV UNIT	STAT
V.AREA30	Area under GZ curve up to 30 deg	0.055	0.333 mrad	OK
V.AREA40	Area under GZ curve up to 40 deg.	0.090	0.506 mrad	OK
V.AREA3040	Area under GZ curve between 30 and 40 deg	0.030	0.173 mrad	OK
V.GZ0.2	Min. GZ > 0.2	0.200	1.135 m	OK
V.MAXGZ25	Max. GZ at an angle > 25 deg.	25.000	30.477 deg	OK
V.GM0.15	GM > 0.15 m	0.150	2.488 m	OK
LR.MAXHEELPASS	Max. heel due to crowding of pass.	10.000	1.553 deg	OK
LR.MAXHEELTURN	Max. heel due to turning	10.000	2.357 deg	OK
LR.IMOWEATHER	IMO weather criterion	1.000	1.839	OK
LR.IMOWINDHEEL1	HEEL < 16 deg	16.000	3.530 deg	OK
LR.IMOWINDHEEL2	HEEL < 80% of FRB immersion	24.685	3.530 deg	OK

Appendix 6. Subdivision of test-case ship POLARTEST

Test case ship POLARTEST watertight subdivision used in the tool verification.



Above: profile, deck 5 and deck 4.



Above: deck 3, deck 2 and deck 1 (double bottom).